final report

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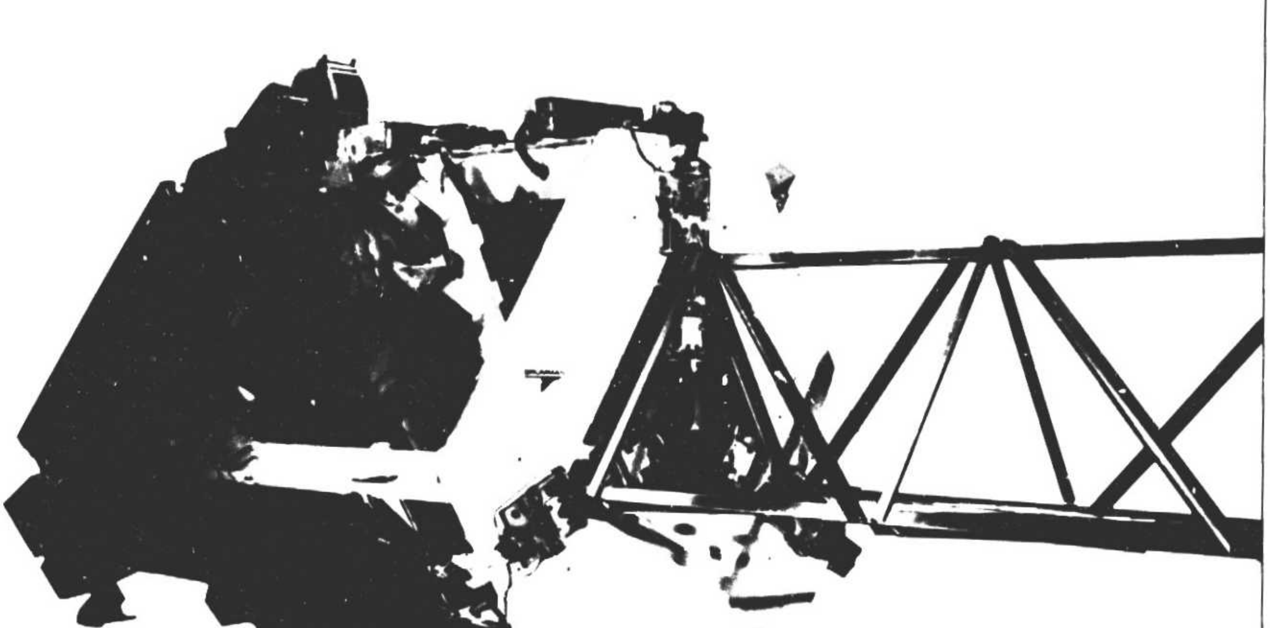
SPACE FABRICATION DEMONSTRATION SYSTEM

executive summary



GRUMMAN AEROSPACE CORPORATION

final report

SPACE FABRICATION DEMONSTRATION SYSTEM

executive summary

prepared for
National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama

Under Contract No. NAS 8-32472
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prepared by
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FOREWORD

This report was prepared by Grumman Aerospace Corporation in fulfillment of NASA Contract NAS 8-32472, Space Fabrication Demonstration System (SFDS) Ground Demonstration Program, Paragraph 3 of the Statement of Work. The SFDS program successfully developed and demonstrated a machine capable of automatically fabricating 1-m deep aluminum beams. This report documents the effort, i.e., analysis and test of the 1-m beam and design, development, fabrication, and verification test of the Automatic Beam Builder (ABB).

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1 - INTRODUCTION

Large area, low density structures are a key technology developmental requirement for the future practical utilization of space. Figure 1-1 illustrates typical systems requiring these large structures. The lightweight 1-m beam, which can be automatically fabricated in space, has emerged as a viable basic building block for construction of these large space structures, i.e., large relector antennas, microwave radiometer antennas, radar astronomy telescopes, solar thermal power systems, photovoltaic solar power systems, microwave power transmission antennas, and a variety of other unmanned applications. This report contains the results of analysis and tests conducted to define the basic 1-m beam configuration required and the design, development, fabrication, and verification tests of the machine required to automatically produce these beams.

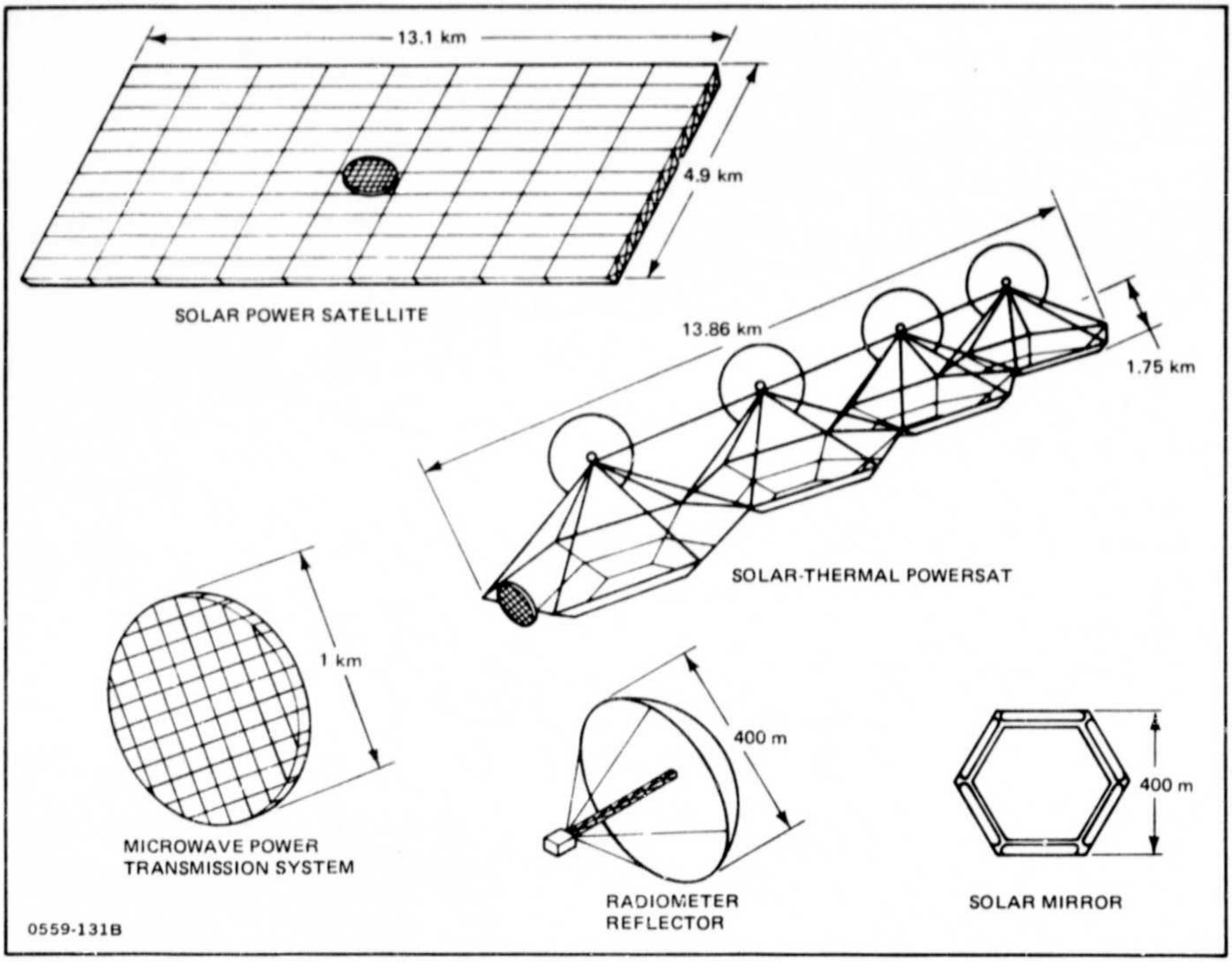


Fig. 1-1 Typical Large Space Structures

2 - STRUCTURAL BEAM

The structural 1-m beam developed for the selected baseline vehicle, the Grumman photovoltaic Satellite Solar Power System (SSPS) was designed for automatic fabrication by the ground demonstration beam builder. Three beams were built and structurally tested; the first two were hand assembled, the third was built by the beam builder without any manual operations. The planned tests simulated the middle bays of the 1-m x 40-m, 26-bay beam under compression load only; the design condition was combined bending and axial load. All three beams were tested to design data derived from the SSPS requirements. All test specimens were structurally tested to loads which exceeded the simulated ultimate design load of 1245 lb (5538 N).

2.1 SATELLITE SOLAR POWER SYSTEM

Design and analytic studies conducted in developing a basic structural member to be built in the automatic beam builder were based on the SSPS configuration (Fig. 2-1).

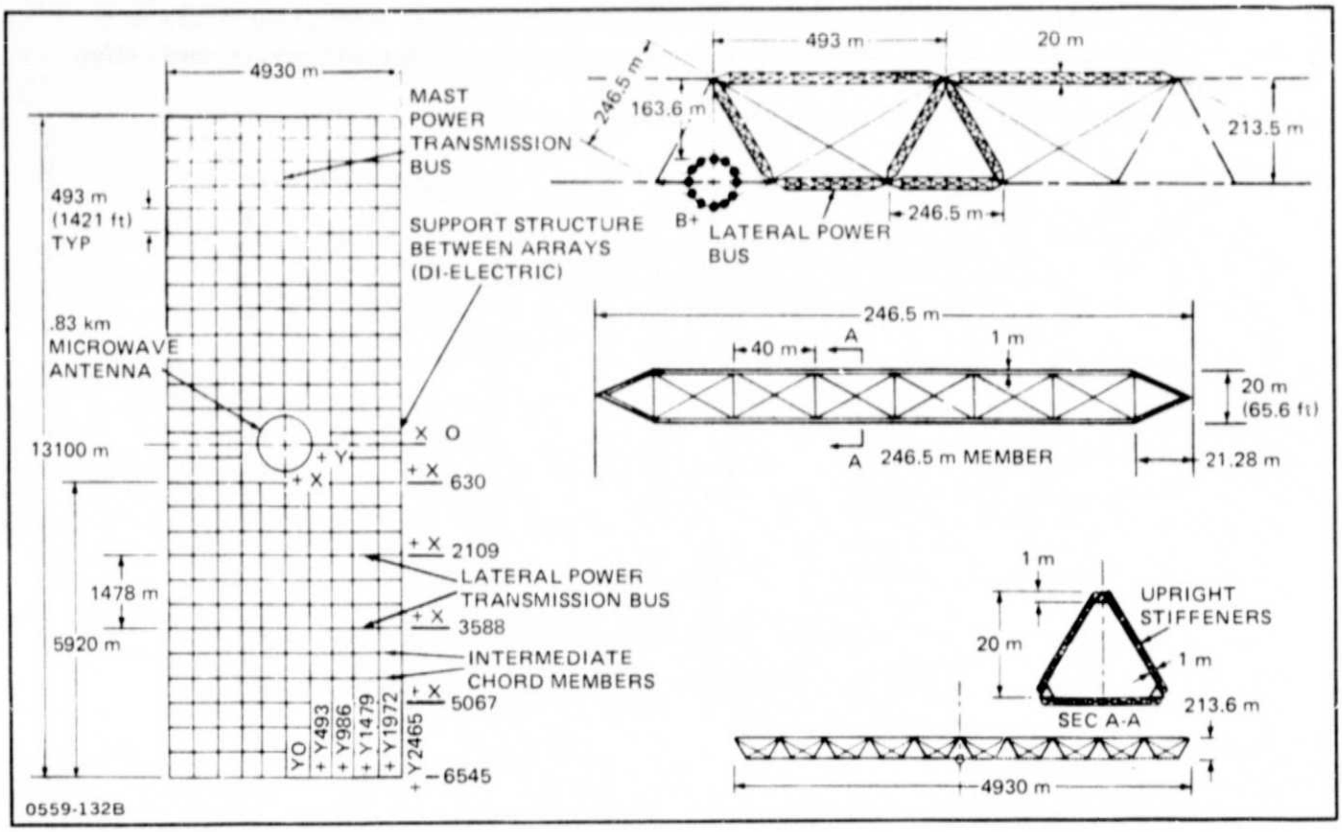


Fig. 2-1 SSPS Structural Arrangement

Some of the pertinent characteristics of SSPS include the following:

- Size: 13.1 km x 4.93 km
- Power: 5 GW
- Orbit: Geosynchronous
- Concentration Ratio: 2.0
- Operating Life: 30 yr
- Structure Natural Frequency: 5.26 CPH bending
- Factor of Safety: 1.40.

The satellite primary structure consists of 20-m x 493-m beams in the X direction; in the Y direction, both 20-m x 493-m and 20-m x 246-m beams are used. The vertical and diagonal members are also 20-m x 246-m beams; the entire system as shown forms a space framework with shear stiffness provided by preloaded tension cables. The entire satellite structure is 213.5-m deep. The main power transmission bus, is structurally integrated with the remainder of the solar array and acts as part of the primary structure.

The 20-m beams consist of three 1-m deep beams each of which is 40-m long (Fig. 2-2) and is supported at the node points by 1-m battens. Shear stiffness is provided by pretensioned crossed cables.

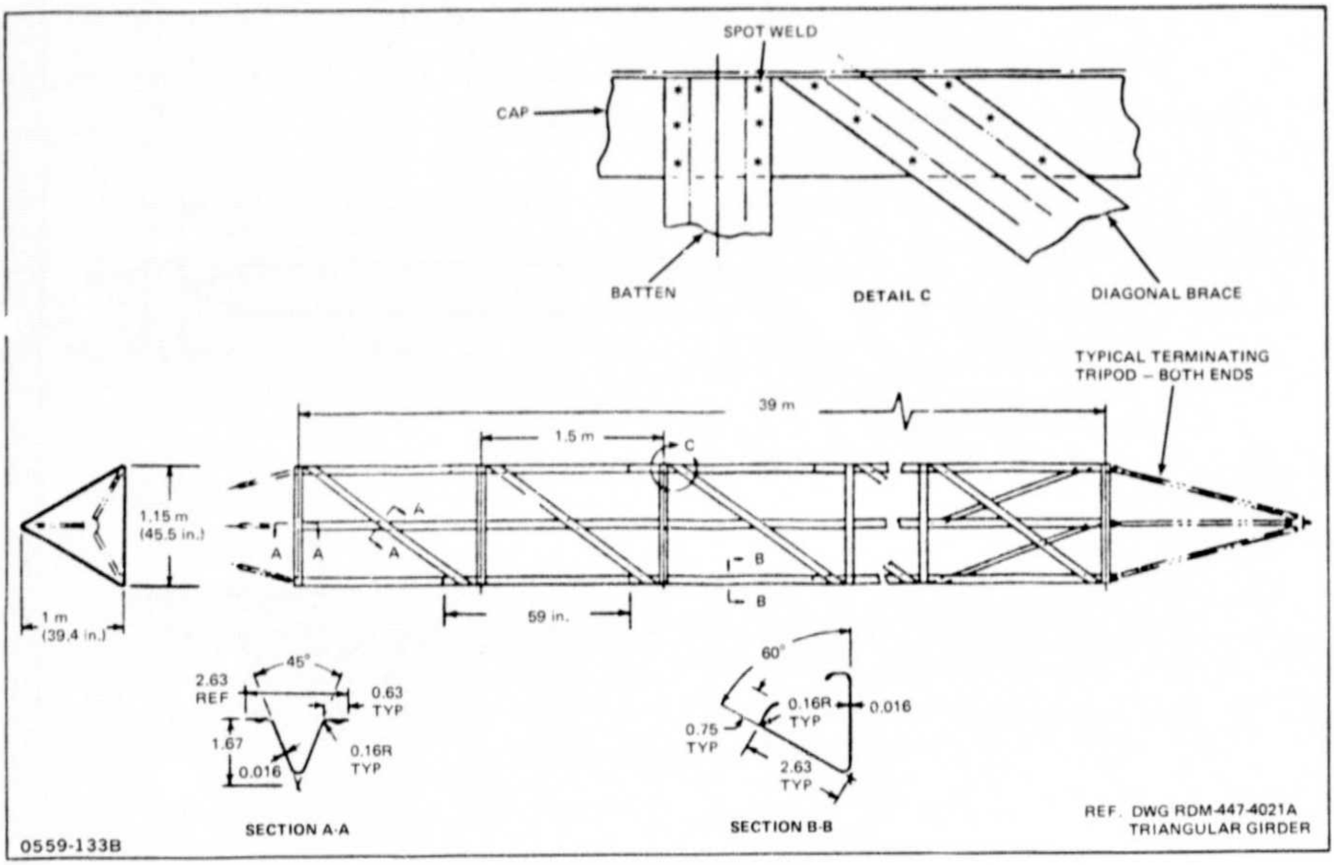


Fig. 2-2 1-m Beam Design

The loads, temperatures, and other environments used in this study to design the structure were taken from the SSPS operational modes only; no attempt was made to design for the various environments experienced during construction, assembly of large modules, and transport to operational orbits. However, analyses were conducted under several related programs to evaluate the structural problems associated with construction and orbital transfer. Initial review of the preliminary study results indicated those design conditions were within the selected structure capability although considerable additional work would have been required to evaluate these areas in greater detail.

2.2 DESIGN LOADS 1-m x 40-m BEAM

The critical loads on the 1-m x 40-m beam are a function of a combination of loads and temperatures applied to the 20-m x 493-m beam of which the 1-m beam is a basic element or cap. Figure 2-3 illustrates the external loading system; in addition, the beam internal loads can be effected by initial manufacturing imperfections such as bowing along the length as shown in the figure. During power generation at geosynchronous orbit, at which time the upper surface is sun oriented, the thermal gradients are in a direction to relieve the lateral beam deflections caused by the reflector load on both the 1-m and 20-m beams. During eclipses, the station keeping maneuver will not be programmed, thus eliminating the bending in the solar array caused by the maneuver.

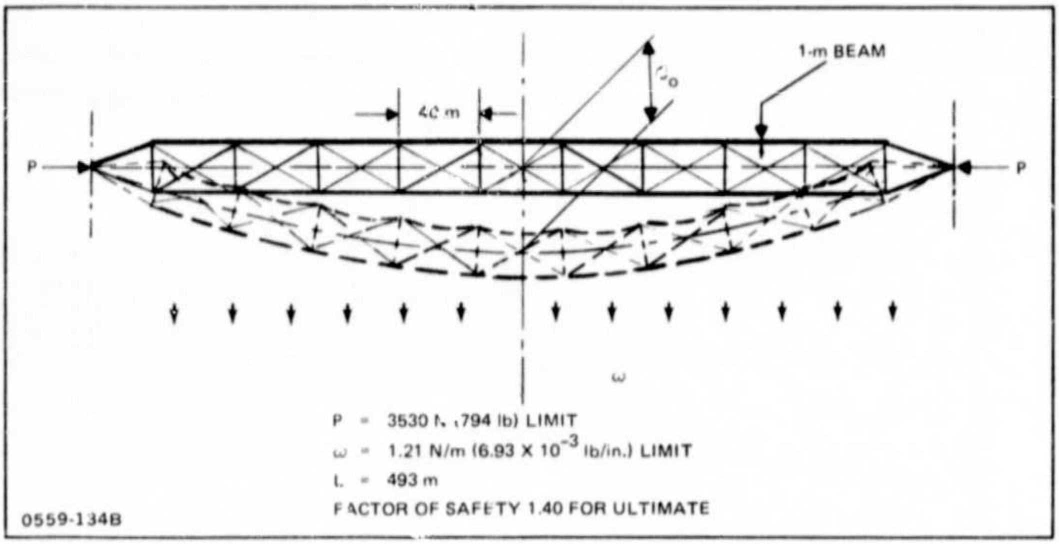


Fig. 2-3 Design Loading Condition 20-m x 493-m Beam

2.3 DESIGN DETAIL 1-m x 40-m BEAM

Figure 2-2 shows the design configuration of the 1-m beam structure; end attachments were not included as part of this study. The caps are roll formed in the beam builder out of 16.18-cm (6.37-in.) x 0.041-cm (0.016-in.) thick 2024-T3 aluminum alloy. Battens and diagonals, which have the same cross section, prefabricated from the same material as the caps; after positioning, are attached to the caps by three spotwelds per leg in the automatic processing operations of the beam builder.

Diagonal members capable of supporting compression loads were selected instead of pretension cross cables in the early phases of beam builder studies. The rationale for selection of a compression capable diagonal was based on avoiding potential problem areas, some of which included the following:

- Do the cross cable and low stiffness batten system have capability to provide sufficient end fixity for a cap which possesses low torsional stiffness characteristics?
- What is the reliability of obtaining a structurally sound single point attachment of a small diameter preloaded wire during beam builder fabrication?
- Does loss of several cable attachments to caps induce lattice column type failure due to inadequate residual stiffness?
- Beam torsional stiffness is markedly greater with stiff diagonal than with crossed cables due to large area difference between the two diagonal design concepts.

Test data, which are discussed below, show that the batten/diagonal design enforces a node at the batten spacing indicating a joint fixity coefficient equal to 4.0 is attained.

The beam unit weight without end attachments is 0.85 lb/ft. (1.26 kg/m).

2.4 THERMAL ANALYSIS (1-m x 40-m BEAM)

A thermal analysis was performed for a 400-km (215 n mi) 28.5° inclination earth oriented orbit at the vernal equinox. Figure 2-4 describes the orientation of the structure in the orbital plane. Early studies of various sur'ace treatments showed that the black anodize coating 1 mil thick, MIL A-8625, with an absorptance to emittance ratio $a/E = 0.86/0.83$, would provide the lowest temperature gradients for the conditions analyzed. This coating can be ground processed on the strip stock and will not be effected during roll forming in orbit. Other orbital orientations could have been chosen which

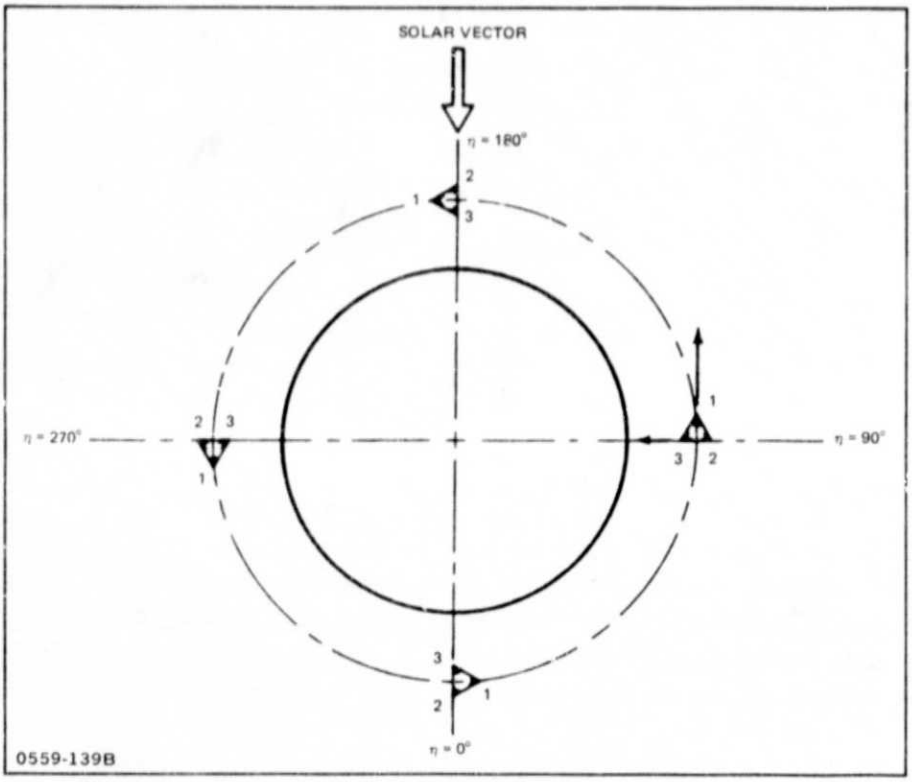


Fig. 2-4 Beam Orbital Orientation

might have resulted in more severe thermal gradients. However, for the known missions at the time of this study, this analysis represented a rational approach to the problem.

Figure 2-5 presents the temperature differences within a cap element and also the weighted average cap temperature for the sun vector oriented at 180° to the beam. The study was done for the sun angle rotated around the structure from 0° to 180°; the 180° position resulted in the largest gradients. Thermal conduction and internal surface radiation were also included in the analysis.

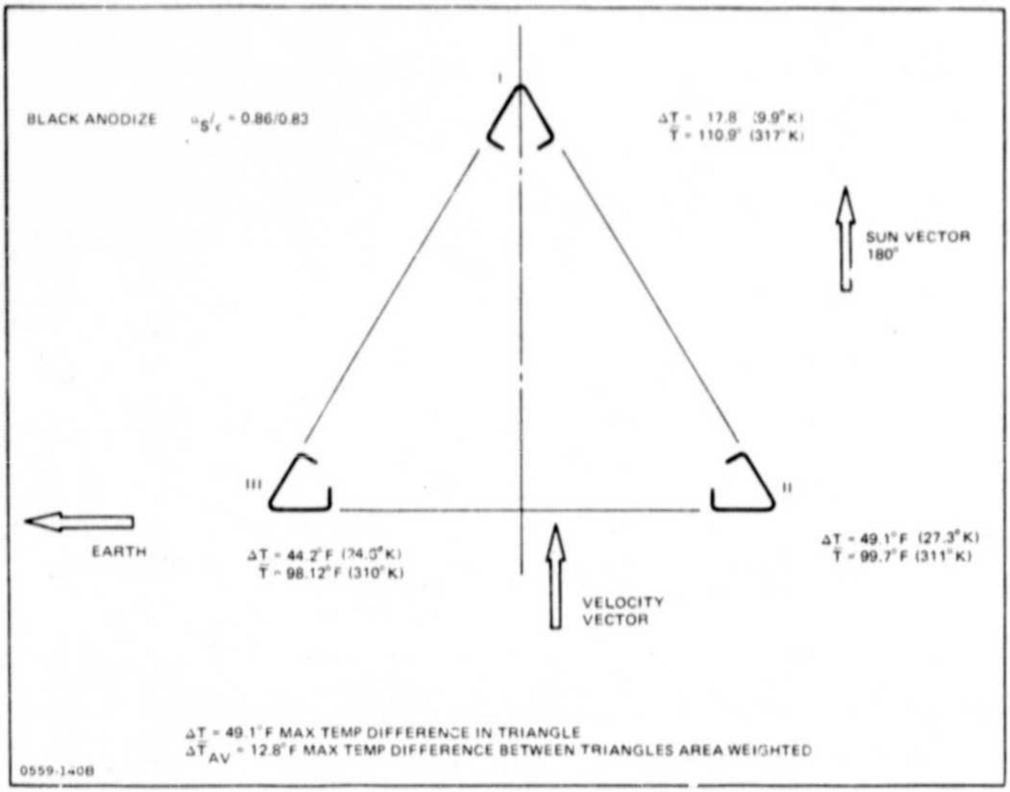


Fig. 2-5 Beam Temperature Response

Thermally induced stresses in the beam caps were evaluated for the 180° sun orientation angle considering two temperature differential effects. The first of these was the non-linear temperature distribution across the cap cross section represented by the temperature curve in Fig. 2-6; the other is the temperature differential between the upper cap at 110.9 °F (317 °K) and the average of the two lower caps at 98.9 °F (310.2 °K). The non-linear temperature gradient in the cross section was analyzed assuming (1) a 1.5-m length cap with unrestrained ends and (2) fixed ends. The results of these analyses are shown in Fig. 2-6 and 2-7. The analyses are based on non-buckled elements of the cap cross section; the peak compression for the unrestrained case is 3.4×10^6 N/m^2 compared to 20×10^6 N/m^2 for the fully restrained boundary condition. The initial buckling for the flat sides occurs at an approximate average stress of 9.4×10^6 N/m^2; the thermally induced stress for the fixed case requires re-estimation based on the redistribution caused by thermal buckling. It is assumed that the stress caused by the non-linear temperature is more closely approximated by the free boundary condition. The estimated stress caused by cap temperature differences is approximately 4.3×10^6 N/m^2; this combined with the local stress gives a total of 7.7×10^6 N/m^2 (1117 psi).

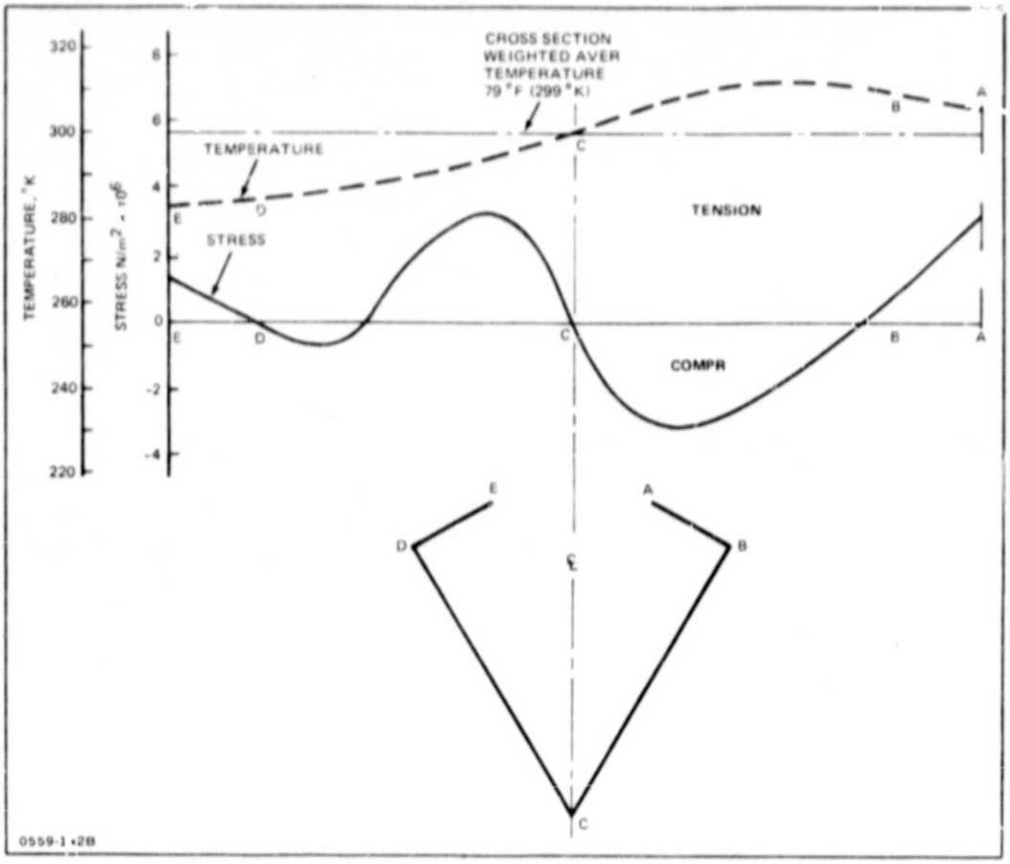


Fig. 2-6 Thermal Stress in 1-1/2-m Long Cap due to Gradient Unrestrained Boundaries

The other significant thermal deformation occurs during the satellite eclipse by the earth's shadow. The temperature excursion is in the order of 115 °F (64 °K). This temperature change can result in a beam total maximum length change of approximately 0.055 m (2.2 in.) depending where in low earth orbit (LEO) the member is fabricated and integrated into the next assembly. The small length change can be corrected for by the design of a length adjustable attachment fitting at each end of the beam.

2.5 BEAM FAILURE MODES

The failure modes of a 1-m x 40-m beam analyzed included the following:

- Cap section, 1.5 m long; critical segment is at center of 40-m beam where compression load is due to combined bending and axial force on 40-m beam
- Diagonal brace
- 40-m beam; load due to combined bending and axial load.

The open cap section (Fig. 2-8) evolved from early in-house studies on triangular cross section beams studied in various materials, including metallics and composites. The design was finalized under study contract NAS8-13876, which was initiated in February 1976. The section is roll formed from 0.016-in. (0.041-cm) 2024-T3 bare aluminum alloy strip stock in the automatic beam builder. Torsion-flexure of

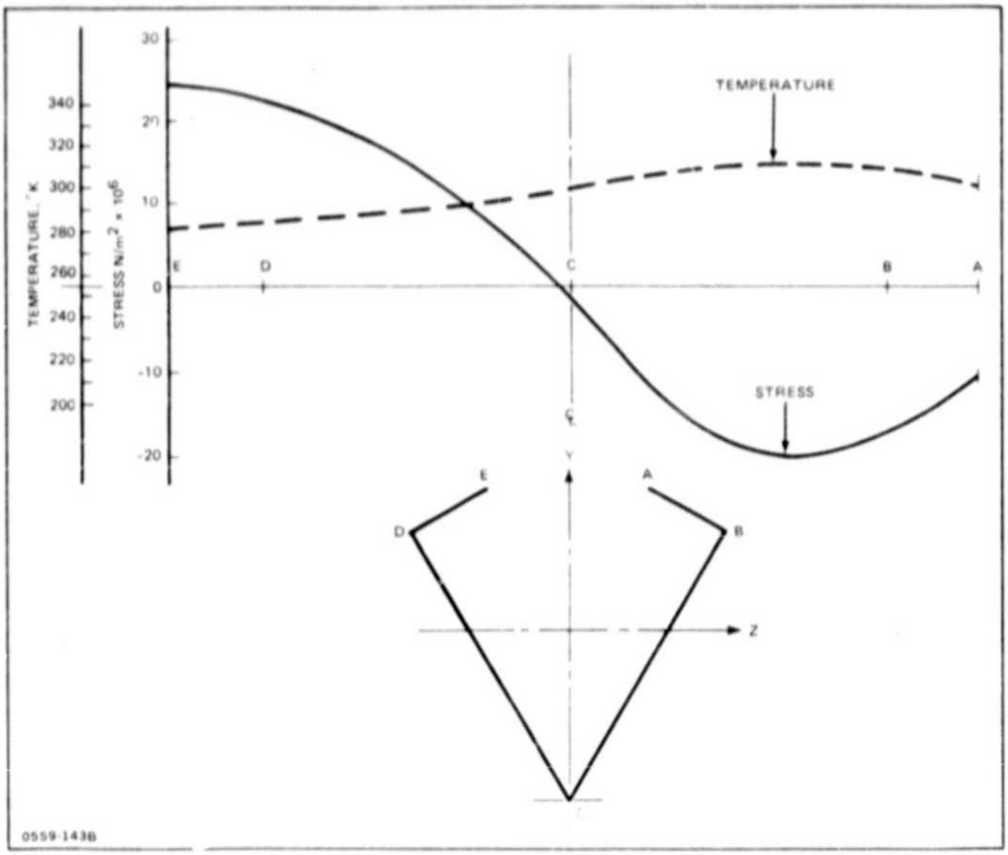


Fig. 2-7 Thermal Stress in 1-1/2-m Long Cap due to Gradient; Fully Restrained in Rotation about Y & Z Axis

the thin walled open cross section column supported at the battens is the primary failure mode based on analytic and test results, and the degree of fixity in bending and torsion provided at the boundaries has a significant effect on the load capability of the column. From data developed under this program and presented below, indications are that the support provided by the vee-hat section batten and diagonal induces a high level of end fixity in both torsion and bending; the effective column length appears to be one-half the batten spacing. Very early studies indicated that cross cable diagonal bracing and battens with very low torsional stiffness would not provide adequate support for the open cap section for the same batten spacing. The cable concept also presents quality assurance problems during automatic fabrication in preventing loss of cable attachment due to misalignment, etc.

2.6 40-m BEAM

The design condition for the 1-m x 40-m beam is a combined axial compression end load of 2558 N ultimate and a lateral distributed load of 1.69 N/m^2.

The beam was analyzed for overall compression stability using a finite-element model; the influence of the simultaneously applied lateral loading was found to have a negligible effect on the buckling load. Figure 2-9 shows the unloaded model and the buckling modes for axial load only and axial load plus lateral load. The buckling load was calculated to be 17485 N compared to an applied load of 2558 N.

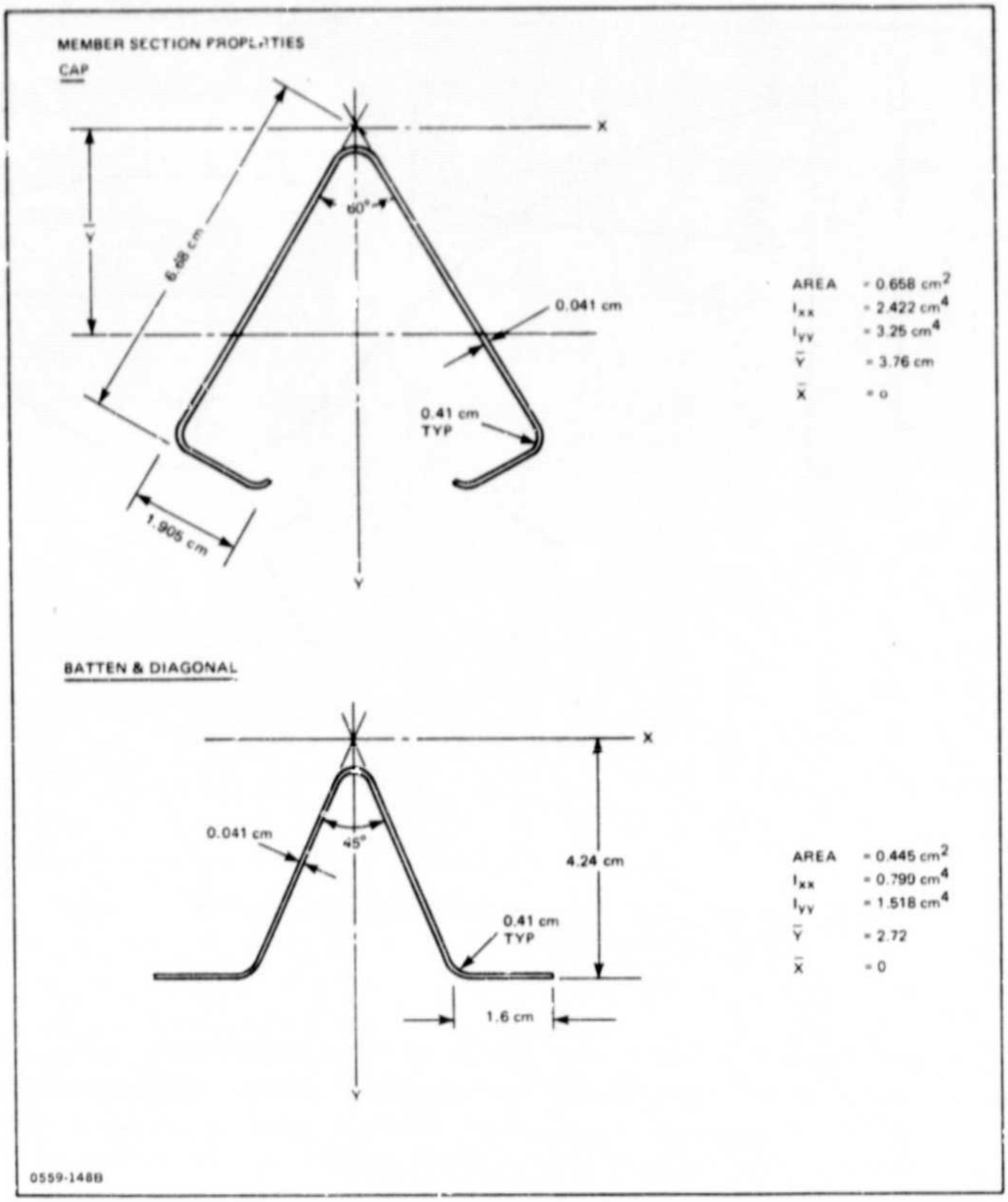


Fig. 2-8 Cap & Batten Cross Sections

Both this analysis and the results of the static finite-element analysis of the beam characteristics indicate an induced torsional deflection under axial load application caused by lateral force components in the diagonals. Static analysis shows the induced rotation to be 0.009 radian for a limit axial compression load of 1829 N. The results of the static axial compression tests on the 6-m long beams show the measured reaction component forces in the plane of the beam cross section induced by loads in the diagnals to be 18 N (4 lb) for limit applied load. These three components produced an external end torque of 17.6 N/m (156 in.-lb). The effect of the end angular rotation did not appreciably reduce the failure load of the 4.5-m beam test specimen described below. This specimen had an upper end condition which was free to translate laterally and rotate about the beam major axis; no external support provision was provided. Based upon the data and tests carried out in developing the 1-m x 40-m beam within the conservative design envelop assumed for the SSPS missions, the basic requirements have been satisfied.

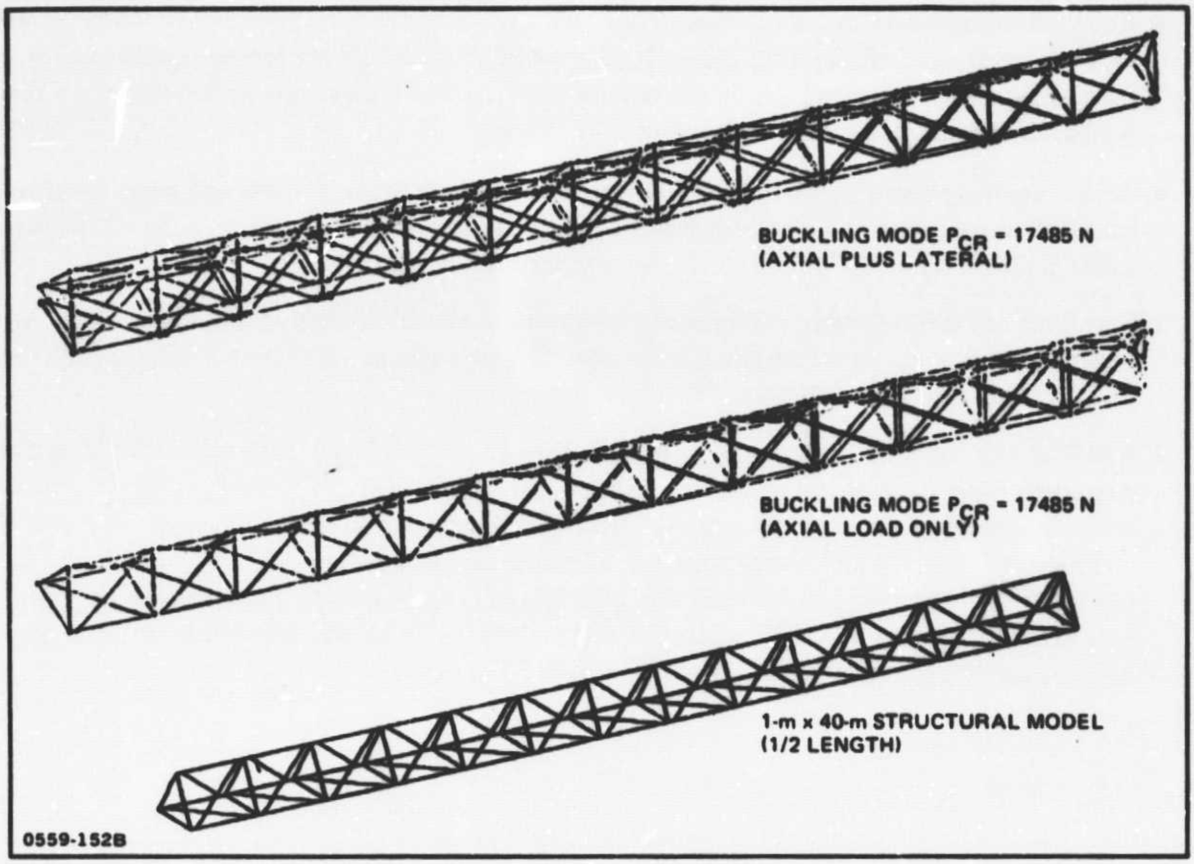


Fig. 2-9 Buckling Modes (1-m x 40-m Beam)

2.7 STRUCTURAL TESTS OF 1-m BEAM

Structural tests were carried out during various stages in the development of Grumman's in-house and funded programs on automatic fabrication in space.

The purpose of these tests was to verify the capability of the cap to carry the design load as represented by beam bending and axial load; the critical section was at the centerline of the 40-m beam. The three compression tests of the beam specimens represent conservative simulations of the actual loading condition; for obvious reasons it was not feasible to conduct the full 40-m beam test in bending and compression. The tests, however, also provide data for a compression – only load condition on the beam in addition to verifying cap columnar stability with actual boundary conditions represented by the battens.

Following is the list of the tests:

- Two 22-in. long cap specimens were tested in compression; the specimens failed at 770 lb (3425 N); failure mode was predominately local crippling because each specimen included a small segment of batten and diagonal; test objective was to evaluate buckling across spotwelds, material 2024-T3 clad
- Two 48-in. long specimens were tested in compression machine; specimens were made of clad 2024-T3 and had slight dimensional difference from final configuration; test was part of in-house study; failure load was 515 lb (2290 N) torsion-flexure mode

- Four 1.5-m caps were tested in compression machine; sections were roll formed 2024–T3 and represented final configuration; failure load was 507 lb (2255 N) for the two good quality specimens; two roll formed specimens with initially rippled flanges due to forming were also tested; their average failure load was 493 lb (2193 N)

- 4.5-m three-bay beam tested in compression, sections were brake formed and beam hand assembled; upper beam end was unrestrained in lateral directions and torsion; failure load was 1260 lb (5604 N) or 420 lb (1868 N) per cap; material clad 2024–T3

- 6-m, four-bay beam tested in compression, sections were roll formed and beam was hand assembled; beam ends were restrained in torsion; failure load was 1507 lb (6703 N) or 502 lb (2234 N) per cap; material 2024–T3

- 6-m four-bay beam tested as in the preceding item above; the beam was built entirely by the automatic beam builder; no manual operations were performed in fabrication; several spotwelds between batten and cap separated just below limit load; in two such locations small "C" clamps were attached and test proceeded to failure; failing load was 1374 lb (6112 N) or 458 lb (2037 N) per cap; the failure was torsion buckling of cap apparently initiated by separation of several spotwelds due to local buckling of cap; failure load was well above the cap ultimate design load of 1245 lb (5538 N) or 415 lb (1846 N) per cap.

3 - AUTOMATIC BEAM BUILDER

Several design development trades were conducted to define the forming, attachment, and automatic control methods. The final Automatic Beam Builder (ABB) design selected is shown in Fig. 3-1 and is comprised of the following subsystems:

- Beam cap member forming is accomplished by three, seven-station rolling mills which progressively form the longitudinal members of the beam from 162-mm wide x 0.4-mm thick flat aluminum 2024T3 stock. The strip stock is fed into the rolling mills from three reels. Each reel can hold 300 m of the flat aluminum stock and can be easily replaced by another when depleted

- Beam cross braces are prefabricated in a conventional manner and stored in magazines for dispensing at the proper time in the correct geometric position. They are made of the same aluminum flat stock as the cap members. Each magazine holds approximately 200 cross braces, enough to make 300 m of beam. As was the case with the aluminum feed reels, these can also be replaced with loaded magazines or alternately may be individually reloaded with prestacked bundles of 50 cross braces

- Fastening of the cross braces to the three caps is accomplished by a single mechanism at each fastening location. With the carriage mechanism holding a cross brace in place on the beam cap member, the clamp/weld block moves into place and clamps the cross brace to the beam cap member, at which time the carriage mechanism releases the cross brace and retracts to its rest position, where it is ready to receive the next cross brace. Once the clamp/weld block is in

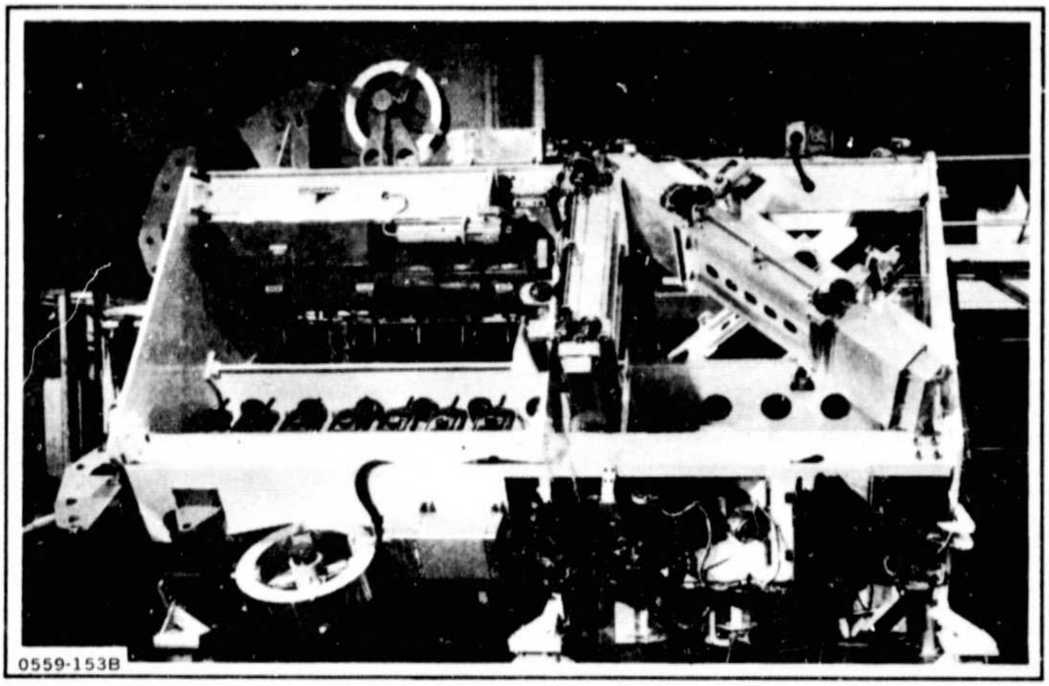


Fig. 3-1 Automatic Beam Builder Ground Demonstration Machine

position clamping the cross brace to the beam cap member, the series spotweld cycle begins with each pair of spotweld electrodes being activated individually until six spotwelds are accomplished at each end of each cross brace. All vertical cross braces are dispensed, clamped, and welded in place before the same fastening sequence takes place for the diagonal cross braces

- Once the desired length of beam has been produced, beam cutoff is accomplished by three guillotines which cut through the three beam cap members simultaneously
- Automatic control is accomplished by means of a simple commercial-type computer which monitors all the operational functions of the aluminum beam builder. Each function from rolling the proper length of beam cap member to form one-beam bay length, 1.5-m, through cross brace dispensing and welding, length of beam produced, and beam cutoff is monitored and registered as completed before the next function is permitted to take place. This monitoring is accomplished by encoders, tachometers, photoelectric sensors, and limit switches strategically placed throughout the machine.

The aluminum beam builder achieved operational capability on May 3, 1978 and since then has automatically produced several hundred meters of 1-m beam section of various bay lengths.

3.1 DESIGN & FABRICATION OBEJCTIVES

Beam builder design and fabrication objectives throughout the program were to provide at minimum cost a fully operational ground Space Fabrication Demonstration System (SFDS), within the principal shuttle constraints, which would automatically produce the previously described 1-m beam. The following general guide lines were used to achieve these objectives:

- Maximum use of off-the-shelf commercial hardware
- Application of high safety factors
- Modular equipment design.

Throughout the design and fabrication tasks the primary approach has been to use existing state of the art proven hardware and commercial expertise to minimize the costs and risks associated with constructing the beam builder.

The safety factors employed for special mechanisms and equipment were approached as in the design of ground operating equipment with little regard toward weight optimization. This was done to minimize analysis costs, expedite construction of the ground demonstration equipment, and place maximum emphasis on the functional aspects of the system. The modular design approach was employed for greater versatility in the system for future structural truss member configurations or modification to the machine.

3.2 GENERAL ARRANGEMENT

The demonstration machine shown in Fig. 3-1 has automatically manufactured the low density, 1-m deep aluminum beams discussed previously. The general arrangement layout for this equipment (Fig. 3-2) identifies the floor space, support equipment, and power services used in the program. The beam builder equipment can be broken into the following principal subsystems:

- Machine structure
- Cap member roll forming
- Brace member storage dispensing
- Beam cutoff
- Controls.

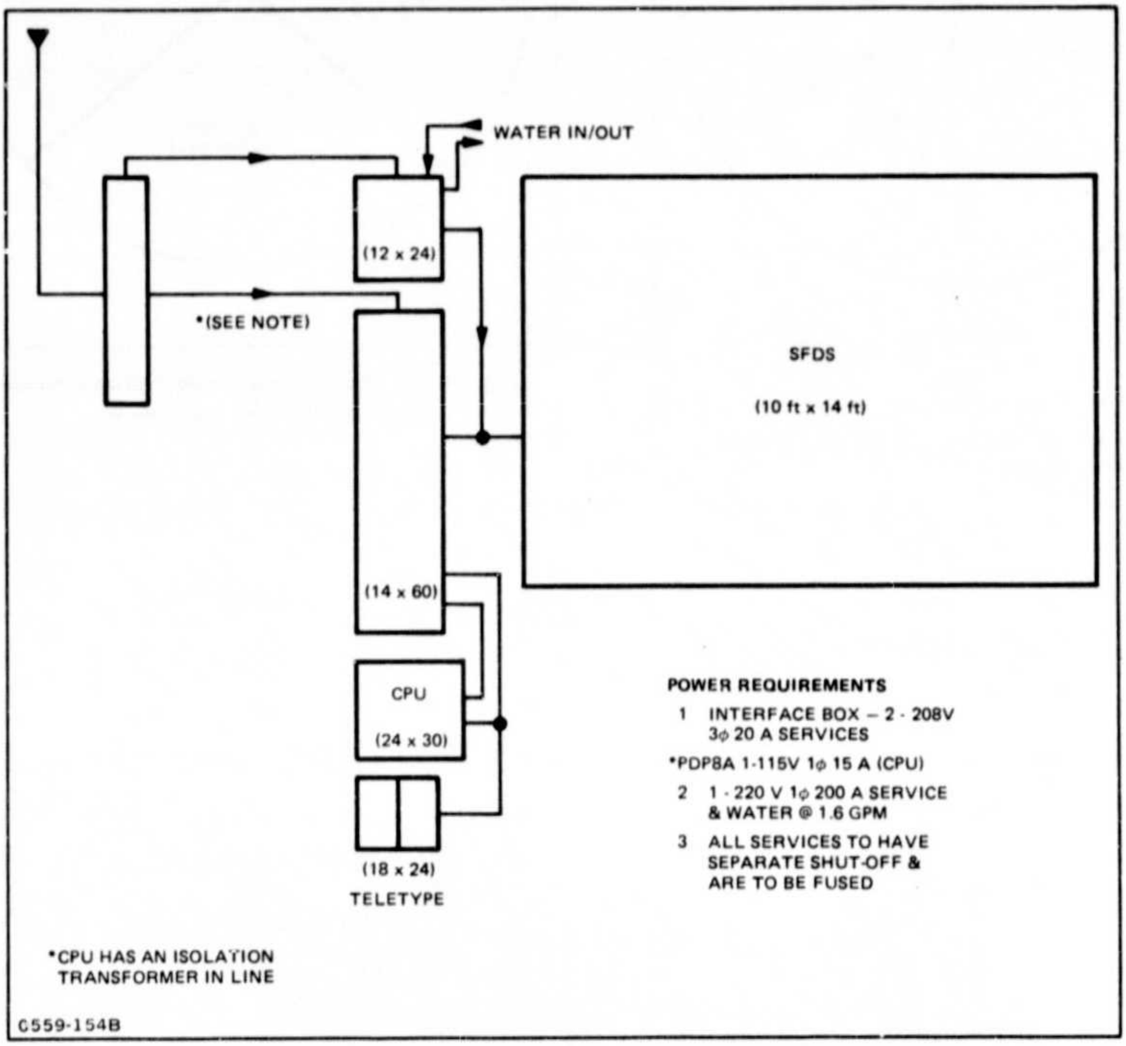


Fig. 3-2 Ground Demonstration Floor Plan & Facility Requirements

The approximate weight distribution of these principal subsystems in the ground demonstration machine is illustrated in Fig. 3-3.

The estimated average power distribution for these principal subsystems in the ground demonstration machine is illustrated in Fig. 3-4.

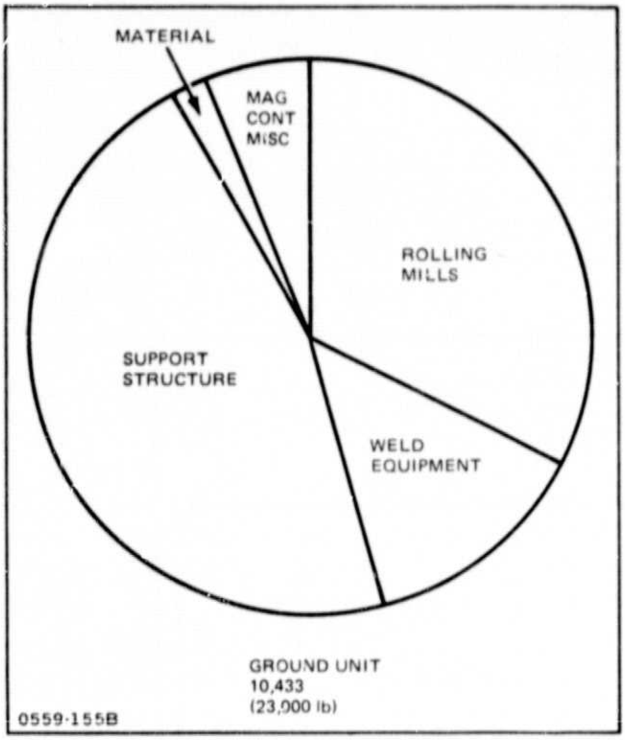


Fig. 3-3 Ground Demonstration System Weight Distribution

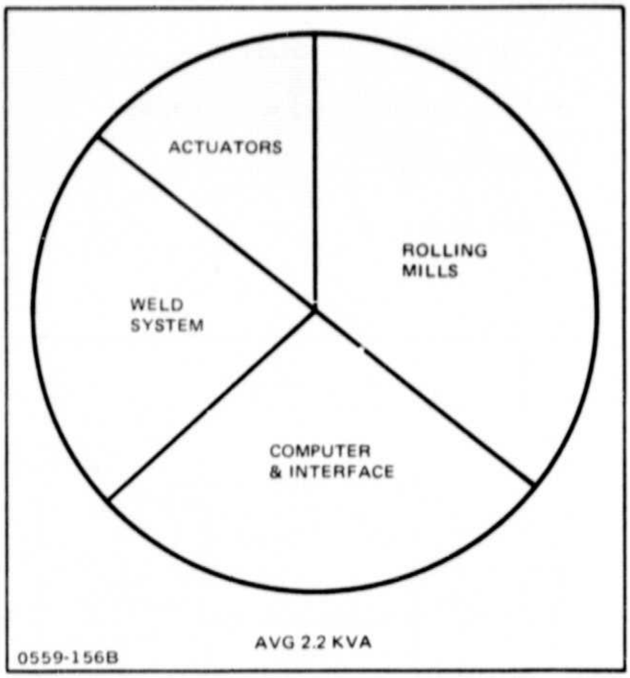


Fig. 3-4 Ground Demonstration System Estimated Average Power Requirements

3.2.1 Machine Structural Subsystem

The ground demonstration machine structure is composed of three major assemblies:

- Base mounting stand, Fig. 3-5
- External support structure, Fig. 3-6
- Internal support structure, Fig. 3-7

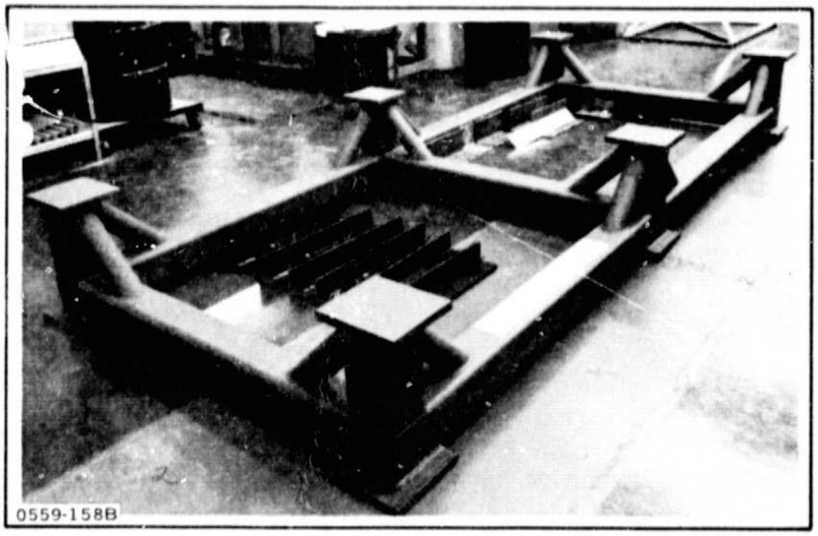


Fig. 3-5 Base Mounting Stand

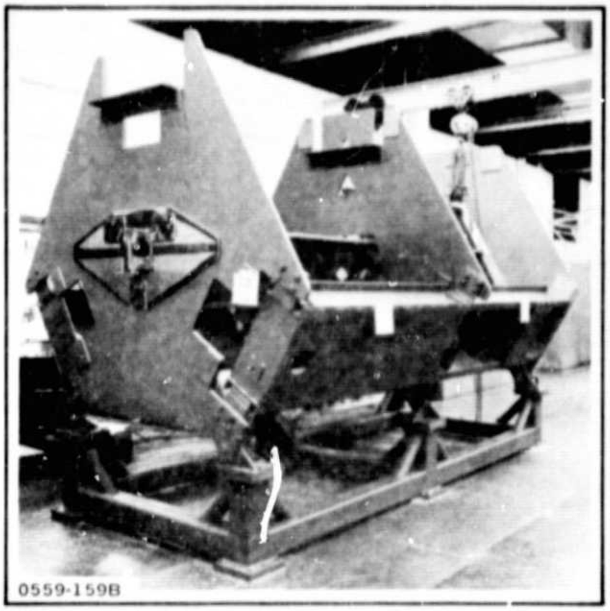


Fig. 3-6 Principal Equipment External Support Structure

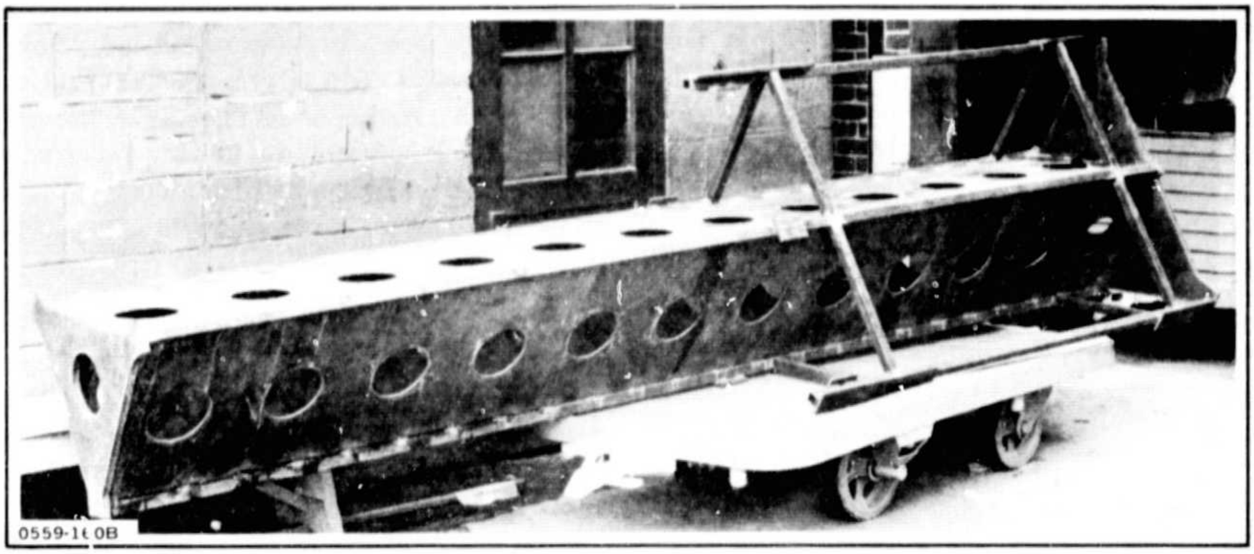


Fig. 3-7 Internal Support Structure

3.2.2 Cap Member Roll Forming Subsystem

The aluminum cap member roll forming subsystem (Fig. 3-8) consists of the following principal components:

- Feed Roller & Guides - The spool storage assembly provides a capability to store up to 1000 ft (300 m) of 0.016-in. (0.41-mm) thick aluminum flat stock. A spring-loaded, cam-driven spool assembly permits easy loading of the slit coils of aluminum strip stock onto the storage spool. Several guide rollers are used to feed the material to the rolling mill strip guide table.
  The cap material is prepared for the roll forming operation by being slit on production slitting

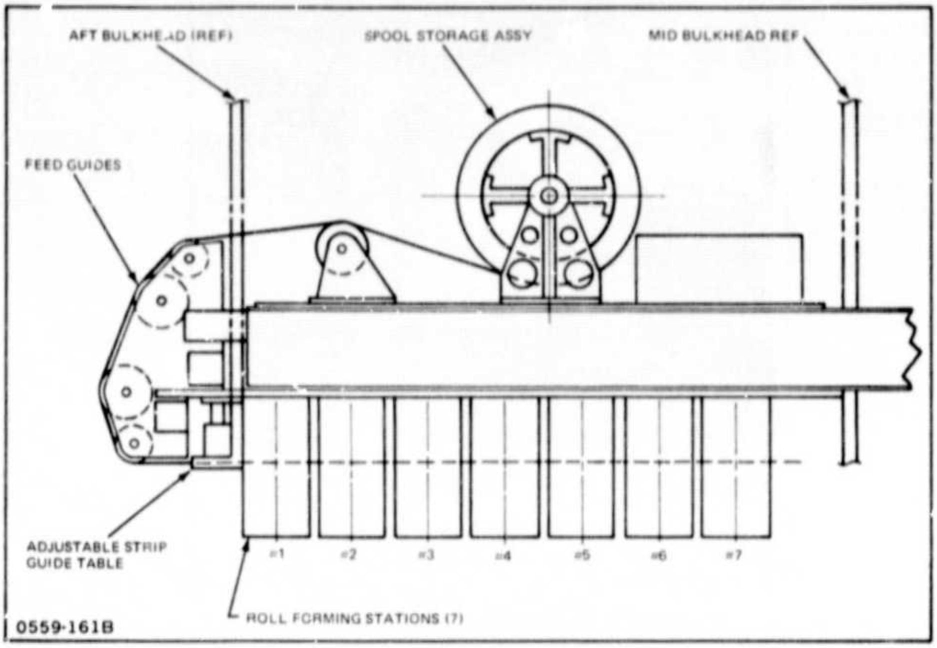


Fig. 3-8 Cap Roll Forming System

equipment to a 6.360-in. (16.154-cm) flat pattern width and recoiled. A rectangular index hole is then die punched into the strip at precisely one-bay intervals 59.005 in. (1.5 m). This hole is used as a control point on the beam to assure proper synchronization of the three cap members.

- Roll Form Equipment - The roll form tooling approach for the program was initially evaluated at Grumman on a production machine (Fig. 3-9) to establish the feasibility of producing a satifactory cap configuration and establish preliminary equipment requirements.

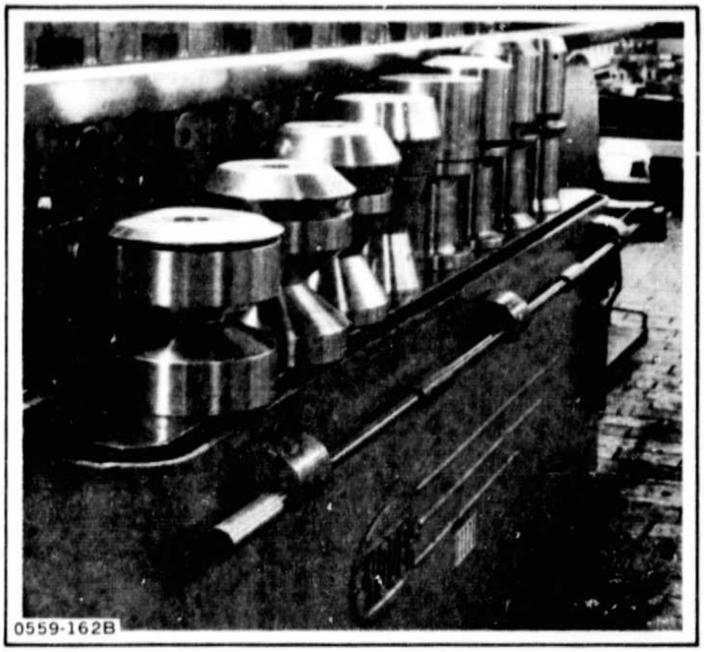


Fig. 3-9 Initial Evolution on Production Equipment

The configuration of the rolls and the number of stations required was established after reviewing the initial roll form tests at Grumman with a design specialist from the Yoder Company. Follow-up roll forming tests with the seven-station configuration (Fig. 3-10) were performed. This setup is compatible to the length constraints as defined in the configuration layout. Positive results were: seven-station configuration is acceptable, i.e., no bow, twist nor flatness anomolies were apparent; and a good geometric configuration was obtained. The seven-step roll forming process is shown in Fig. 3-11. These tests also illustrated that bending of the flange angle must be distributed over five stations. A minor wave condition noted in the return flange was addressed by modifying two rolling stations to redistribute the workload of station five.

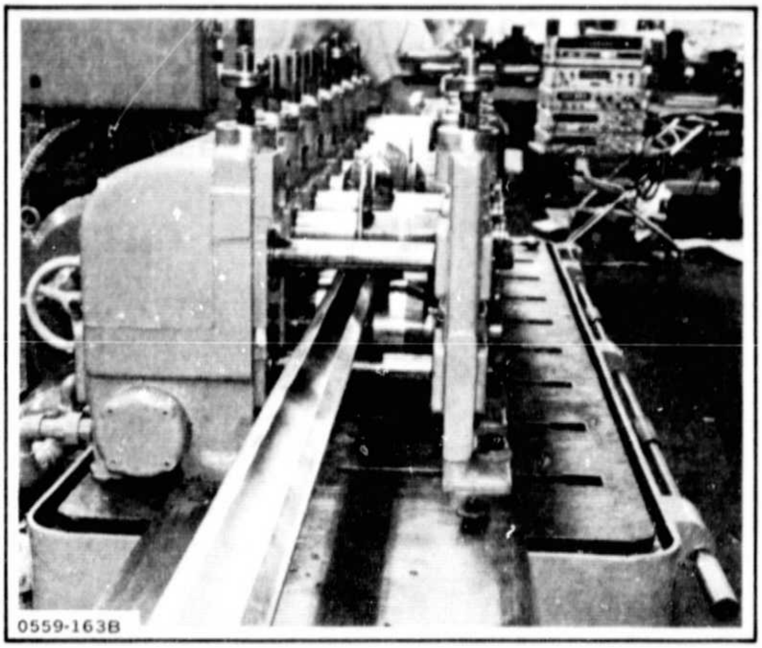


Fig. 3-10 Seven-Station Roll Form Tests

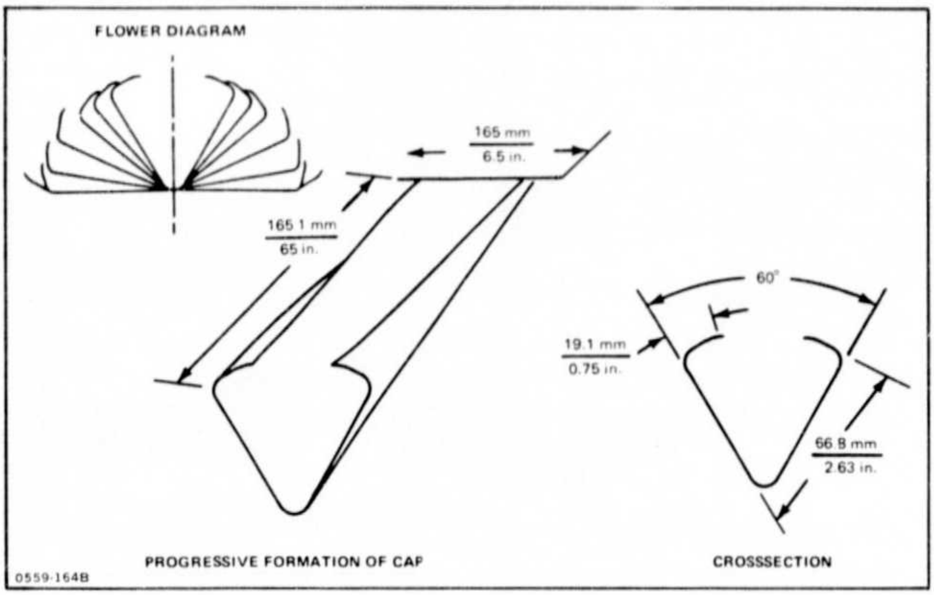


Fig. 3-12 Seven-Station Progressive Roll Form Steps

During the final evaluation tests with the rolling mills installed, a minor crimp in this flange occurred in the cap being produced by the right hand rolling mill. The defect would occur when the cap passed over the weld guide block and could not be corrected by realignment in the SFDS. The waviness of this flange was structurally evaluated and found to have negligible impact on the structural capability of the cap member. Prior to final delivery to MSFC the right hand rolling mill was sent to the Yoder Company to correct this anomaly.

3.2.3 Brace Member Storage Dispensing Subsystem

The function of this subsystem is two-fold:

- Store the ground fabricated brace members
- Select a brace from the stored members and transport it into position on the caps.

In contrast to the continuous cap manufacturing approach discussed in the previous subsection, the relatively shorter brace members were prefabricated in a conventional production facility and stored in a magazine to be dispensed at the proper time. The specific design approach selected for use in the beam builder incorporates the following principal features:

- Modular design
- Helix selector
- Separate brace transporter.

The magazine design was determined after evaluating two approaches. The initial approach incorporated both the brace transport mechanism and magazine into one unit. A functional mockup of the unit was built (Fig. 3-12) and tested.

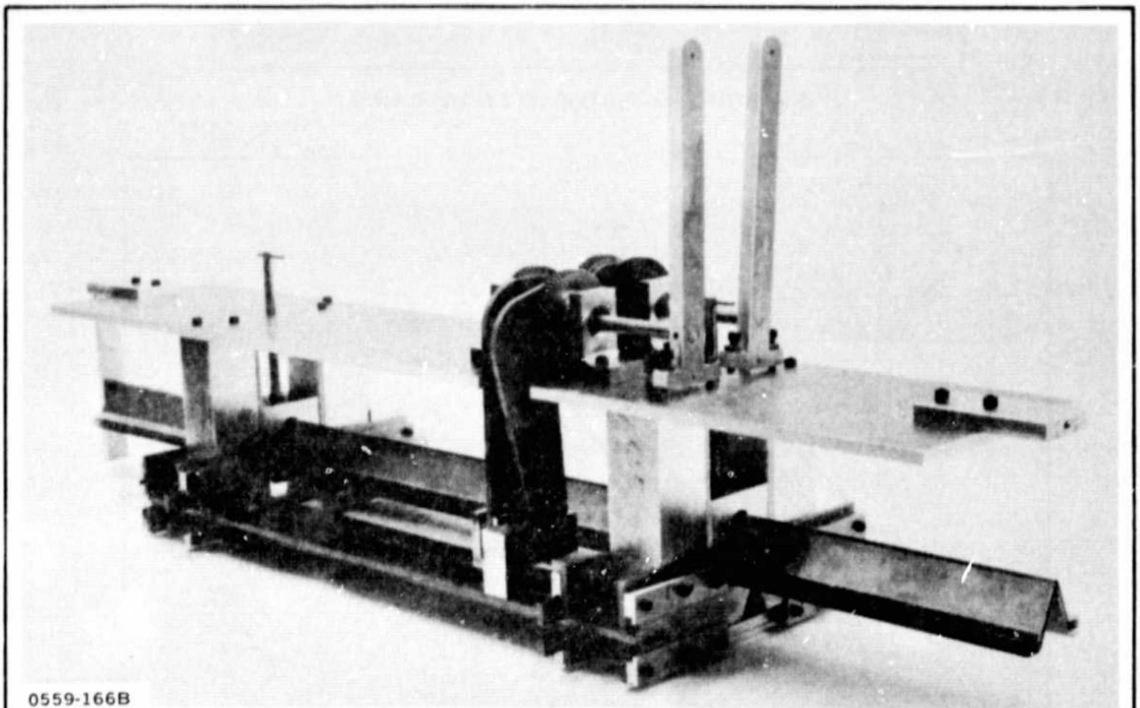


Fig. 3-12 Magazine/Dispensing Mechanism Fixture

This approach was modified as a result of evaluation tests with the mockup and a need for a more compact modular unit which could be removed from the basic machine. The final design is shown in Fig. 3-13. It utilizes a helix selection for dispensing braces. The system operates in the following manner:

- The brace feed spring presses the stack of braces against the upper portion of four single-turn helixes
- The brace transporter gripper is rotated 90° to act as a stop for the next brace to be dispensed
- The helixes are rotated 360° with the leading edge of each helix acting as a selector which separates the first brace from the remainder of the stack by about 3/8-in. to the surface of the brace transport gripper mechanism
- The gripper fingers are closed on the brace capturing the brace flange at four points
- The transporter with the brace is driven by a ball screw so the brace is in contact with the cap members
- The brace is then clamped to the cap with a weld clamp mechanism
- The gripper fingers are retracted releasing the brace flange
- The gripper is rotated 90° so the mechanism will clear the brace and can be retracted to its park position.

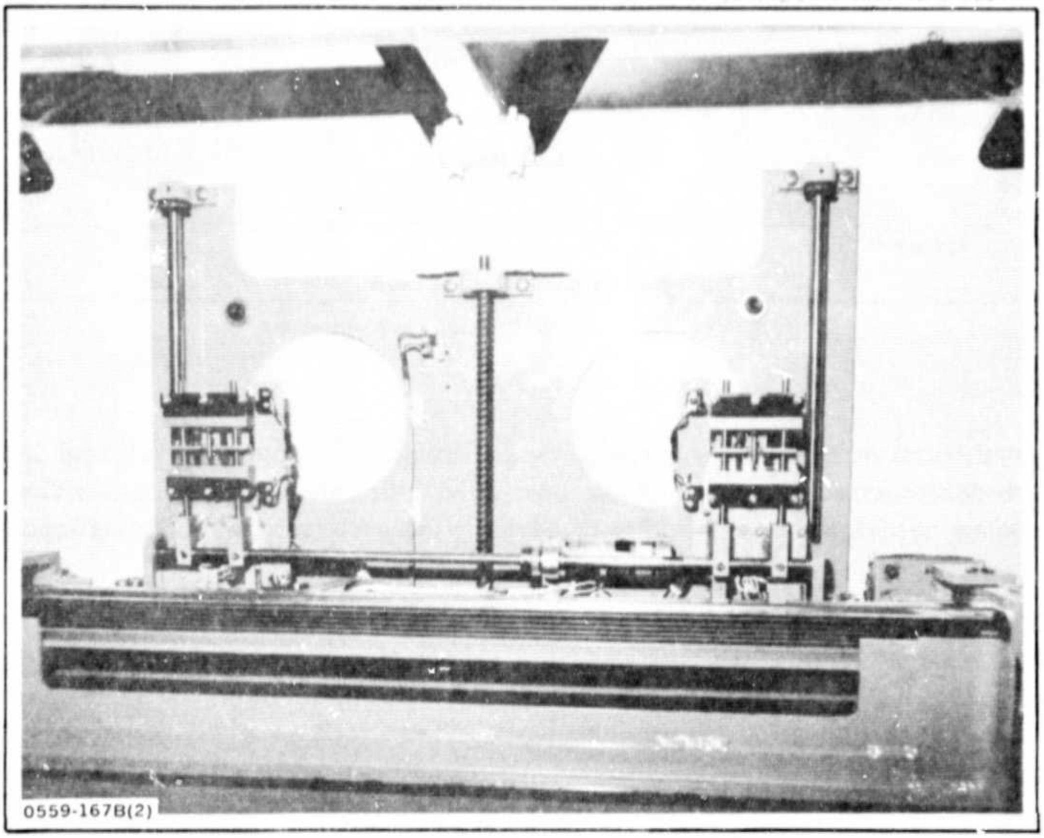


Fig. 3-13 Brace Transporter Carriage

3.2.4 Brace Clampup & Attachment Subsystem

This subsystem (Fig. 3-14) was designed and built to perform two primary functions:

- Clamp the brace members with sufficient force to offset weld electrode clamp forces
- Resistance spotweld the brace members to the caps.

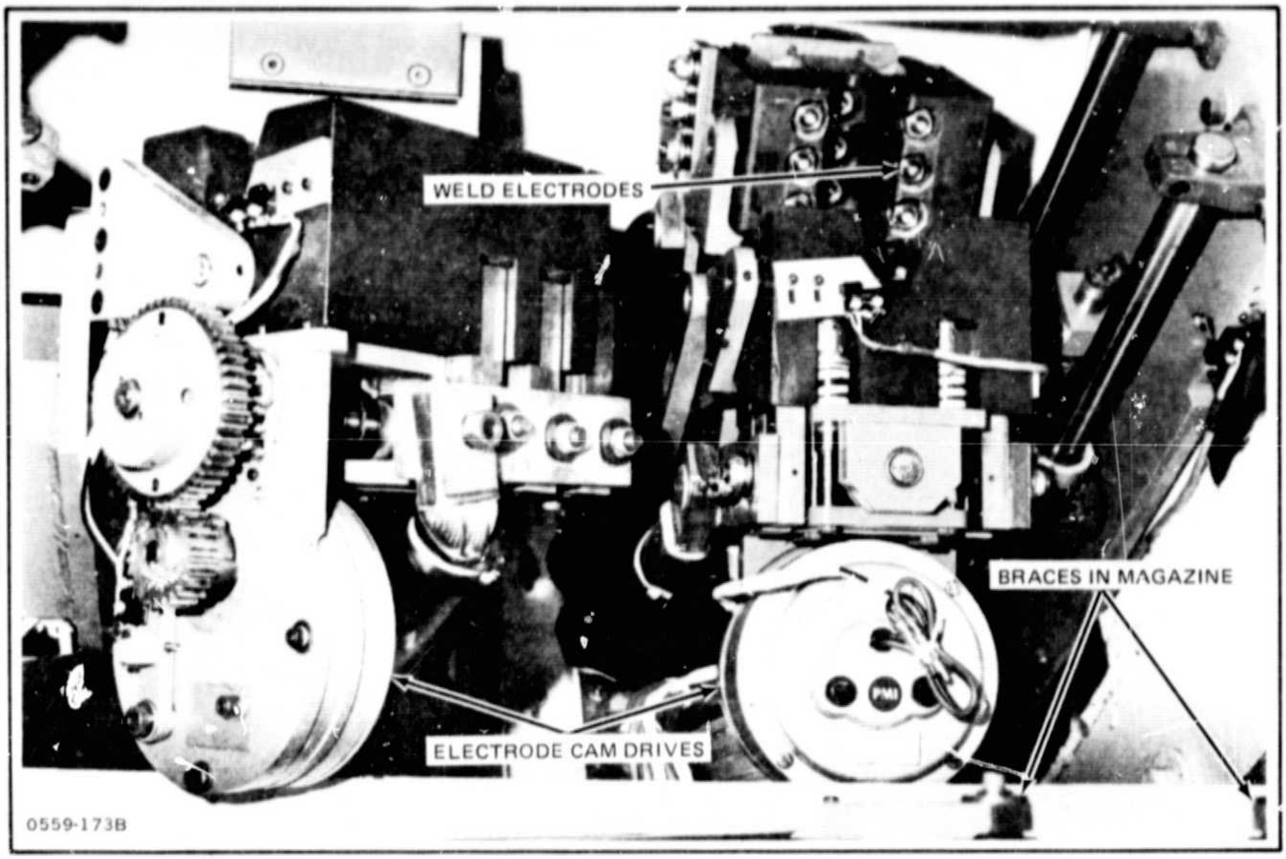


Fig. 3-14 Brace Clampup Attachment Subsystem

These functions are accomplished through the integration of the following principal devices: a mechanical scissor clamp mechanism, cam actuated weld electrodes, and resistance spotwelding system. After evaluating several alternatives, discussed later in this paragraph, the following approach was used:

- Once the brace members have been transported from the magazine brace dispenser to the cap, the clamp mechanism is advanced to a fixed position. A scissor mechanism dirven by a ball screw is used to apply the clamping force through a pair of polyurethane plastic blocks to the brace and cap. An internal copper guide block prevents collapse of the cap member during clampup.
- After the three vertical or diagonal brace members are clamped, a cam mechanism is actuated to permit individual pairs of spring loaded weld electrodes to be driven into the brace member.

The one pair of electrodes in contact provide the only complete circuit (Fig. 3-15) through the brace and cap, with the copper guide bar acting as a shunt from one spot to the other. As each pair of welds are produced the cam is cycled introducing the next pair of electrodes into the circuit until all electrodes have been fired

- The clamp mechanism scissor is opened and the entire mechanism retracted clear of the cap so the next brace can be advanced into position.

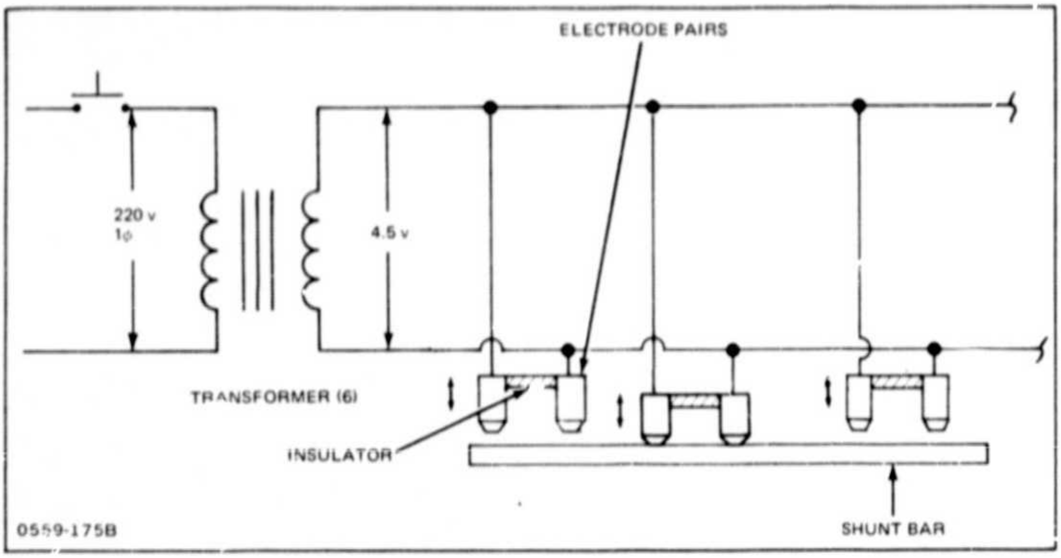


Fig. 3-15 Welding Process Schematic

Resistance spotwelding was selected as the attachment technique on the ground demonstration system for the following reasons:

- Process is a common commercially available approach to attaching thin gage metal components
- Considerable experience has been accumulated in aerospace industry using this process
- Process has a fast cycle time
- Process does not have any obvious space environment deterrents, such as material vaporization
- Electrodes are small and compatible with automated mechanisms.

The equipment used was a Sciaky single direct energy system with SCR contactors with six 220-v input 63 KVA transformers with an output rating of 4.5 v, 14,000 A. Six 63 KVA transformers were used instead of one 75 KVA unit to reduce the electrical losses in the power cables to the weld electrodes.

3.2.4.1 Weld Pattern – During the preliminary design of the ground demonstration equipment a choice between a six-weld or eight-weld pattern was required to determine final mechanism design. The four-weld pattern would require an extra movement because four electrodes with their springs would not fit in the attachment space required and the pattern would have been attained with two firings of the same set of electrodes per joint. A pattern of six electrodes could be spaced so that a single firing position would provide the necessary attachment pattern. In order to check the structural integrity of the six-spot-weld configuration, six and eight spotwelded components were fabricated from 0.016-in. thick, 2024-T3 clad material and tested.

Three components were fabricated from 0.016-in. thick, 2024-T3 clad material and tested per the general arrangement shown in Fig. 3-16. Each component was compression loaded 15 times up to 300-lb (limit load), then to ultimate failure (Fig. 3-17).

Metallographic examination of the configuration No. 2 diagonal brace attachment welds (MP-AMPD-MO-77-133) indicated that buckling failure did not have a detrimental effect on the integrity of the spotweld

Based upon the test results the six-spot, 1.375-in. spacing weld configuration was selected.

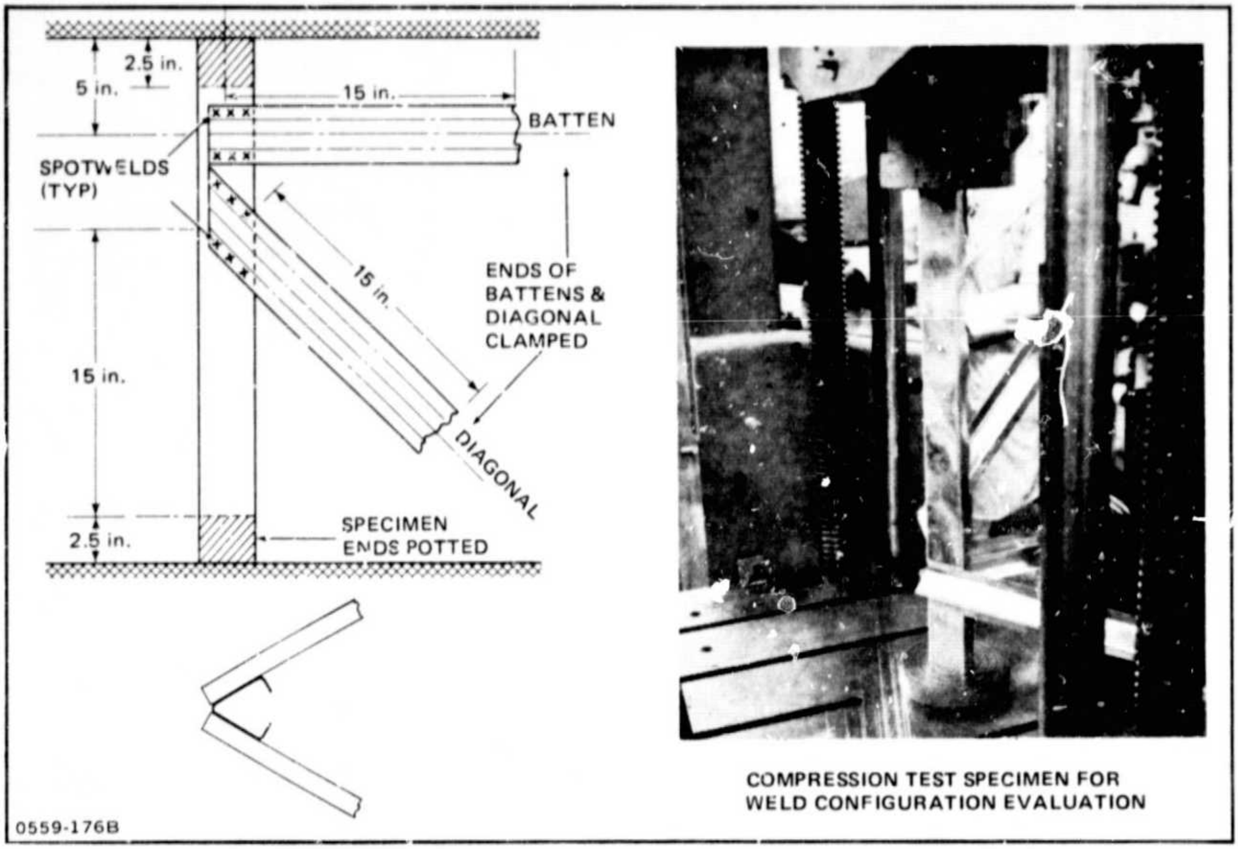


Fig. 3-16 Component Test Arrangement

3.2.4.2 Alternate Welding Approach – Ultrasonic welding was considered as an alternate approach. This system had the advantage of requiring less power, but due to accessibility problems multiple heads with modified anvils would be required. Such a change would increase the equipment cost significantly over that for resistance welding.

Tests were conducted using to ultrasonic welding machines, i.e.:

- Branson 3000 W, Model 3301
- Sonobond, M-1200 Bench Welder.

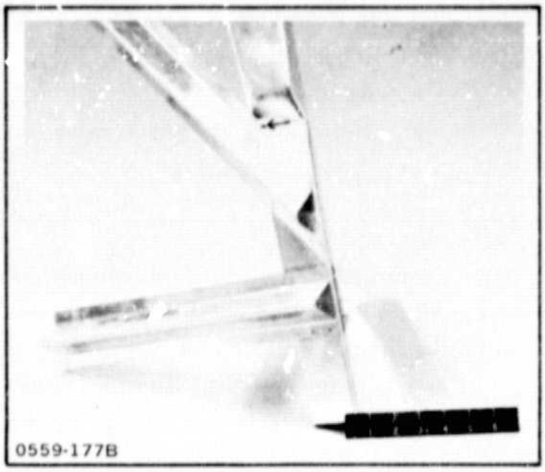
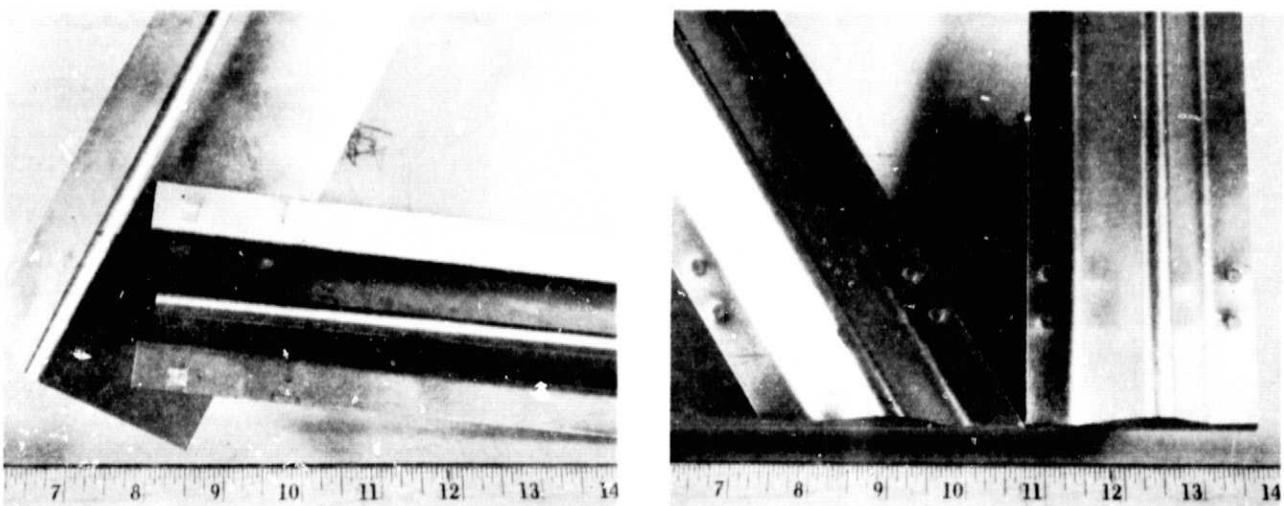


Fig. 3-17 Six Weld/Joint Test Specimen

Photographs of the ultrasonic welds produced by these machines are shown in Fig. 3-18.

Although these initial results were generally considered acceptable, the following major problem areas would have to be fully addressed for solutions where possible:

- Tip and mandrel sticking occurred frequently (mostly tip)
- Excessive surface identation (particularly on Sonobond welds)
- Limited accessibility in truss welding
- High cost of equipment.



0559-179B (BRANSON) (SONOBOND)

Fig. 3-18 Ultrasonic Spotwelding

The resulting peel tests showed that Sonobond welds averaged 26.8 lb and the Branson welds around 10 lb. In the case of lap shears about 50% of the welds pulled nuggets for both machines. In the case of the peels, only one out of five was a shear failure; the remainder pulled nuggets as partial nuggets. Typical lap shear and peel samples of the Sonobond welds were given to the NASA-MSFC representatives.

3.2.5 Beam Cutoff

The output beam is cut to length using the truss cutoff mechanism shown in Fig. 3-19. This device is comprised of a screw-driven guillotine and a lower die which has both an internal support mandrel and a retractable die section. The truss cutoff utilizes a double shear approach to severing the beam cap member. A slice of 0.170-in. wide cap material is removed during the shearing operation; therefore, neither the fabricated beam nor the formed cap have to be displaced. The excess material is captured in a cavity in the lower die. In addition to imparting no relative motion to the cap and beam, the principal advantages of this approach are absence of extraneous particles and a clean cut.

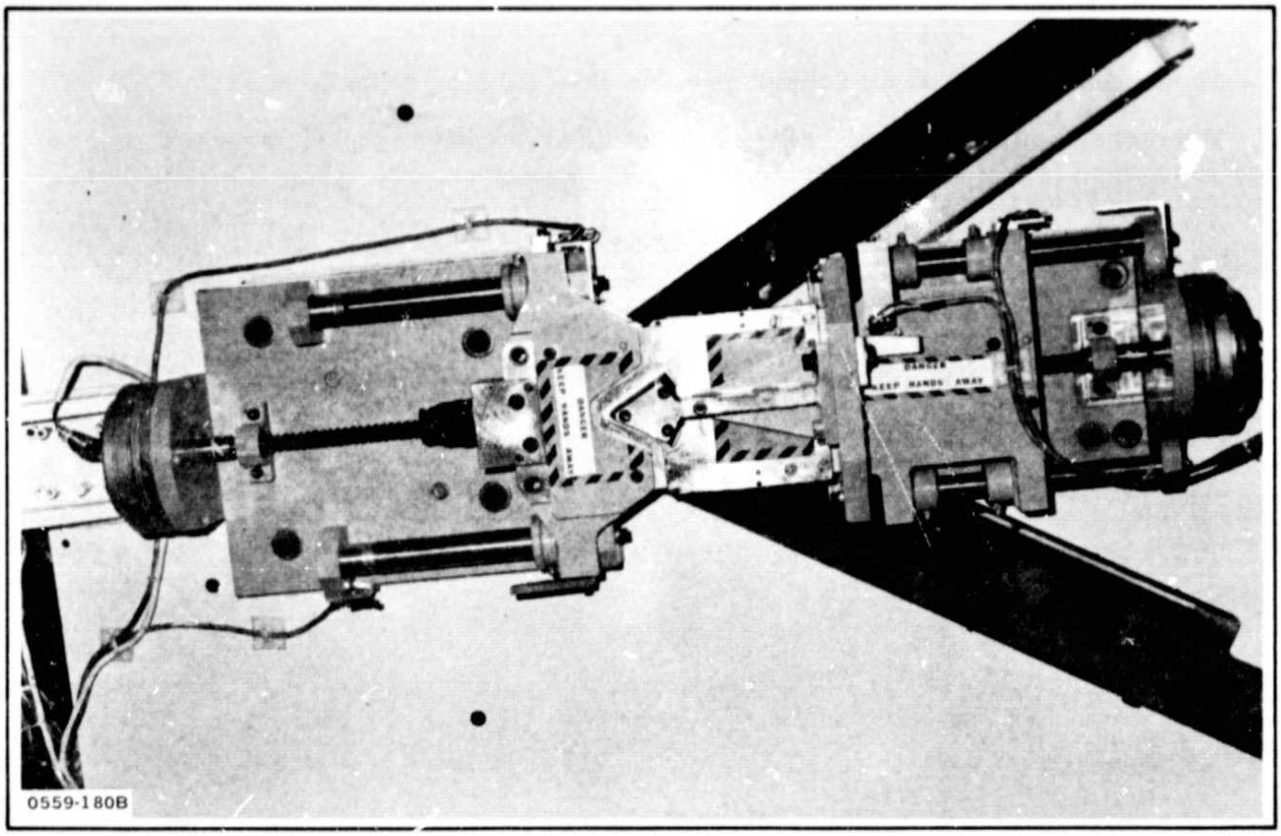


Fig. 3-19 Shear Assembly

3.2.6 Controls

The control system for the Space Fabrication Demonstration System is responsible for overall automatic control of beam fabrication (Fig. 3-20). As such it drives each of the three rolling mills in closely synchronized fashion to ensure that the three associated cap sections are formed at the same rate and have the same length. In addition, the control system directs the sequence for the assembly/ fastening cycle which consists of alternating stops of cap positioning, fastening, and ultimately cutoff. The heart of the system is a Digital Equipment Corporation PDP-8A computer. The PDP-8A was chosen for its proven off-the-shelf reliability and large library of previously developed and debugged software.

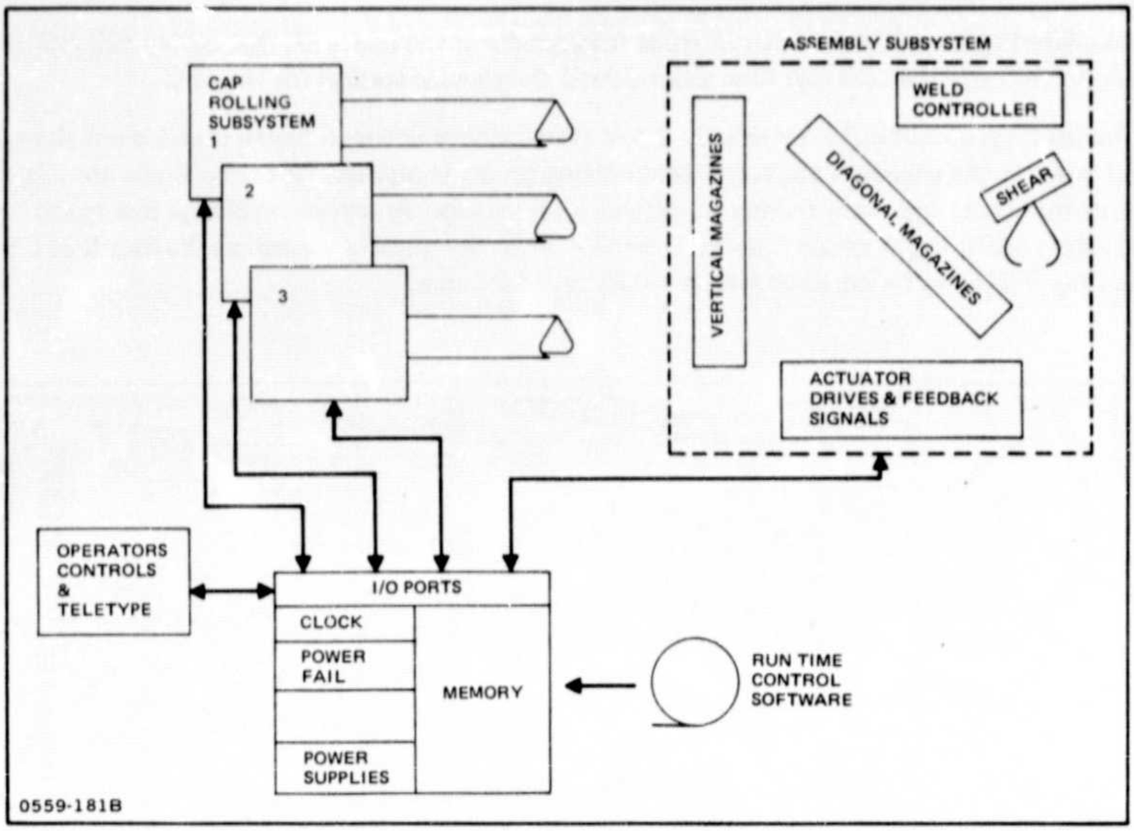


Fig. 3-20 Control System Block Diagram

3.2.6.1 Rolling Mill Control – The cap positioning controls drive each rolling mill so that the caps are formed at precisely the same rate and so that the rolled lengths are equal to fastening the vertical and digital supports. It accomplishes this by sending out a synchronized serial pulse train to each of three servo translators. It is known that there is a slippage between rollers and cap members and that this slippage is not consistant. Therefore, a mechanism is employed to determine this slippage on the fly; that is, while the caps are being formed. The technique uses an encoder feedback device driven by the cap material being fed through the roller.

There is no stop/start motion involved. After the motion start of the beginning of cap formation, they do not stop until they have formed the one bay length of section.

In addition to ensuring that the final position is reached by the three caps at the same time, the controller makes forced corrections to bring the caps into synchronization as soon as possible by withholding pulses to one or two of the rolling mills. Thus, for a case when the slippage factor of one or more rolling mills changed suddenly, the controller would try to re-synchronize the caps quickly without simply re-scaling to ensure that the final position was correct.

3.2.6.2 Controlling Bay Length – A check on the accuracy of the encoder measurement is also made on the fly. This may be necessary due to slippage of the friction drive wheel used to couple the encoder to the material. It also compensates for changes in the dimension of the encoder drive wheel. The method used consists of putting slots in each of the caps spaced one bay length apart. A light source and photo detector arrangement is used to determine when these slots pass the viewing station. Each time a

slot passes a viewing station, the computer reads the encoder associated with that rolling mill and compares the reading to the one taken the last time a slot passed the viewing station for that mill.

The readings should differ by exactly 1.5 m (the distance between bays). If this is not the case, the weight given to the encoder counts will be modified by the computer. Of course limits are placed on the amounts that these and other factors are permitted to change. An excessive change in a factor is a sign of a system malfunction which must be corrected. With this control technique the length of a ten-bay beam (Fig. 3-21) was found to be within ± 0.03 in. (± 0.8 mm)

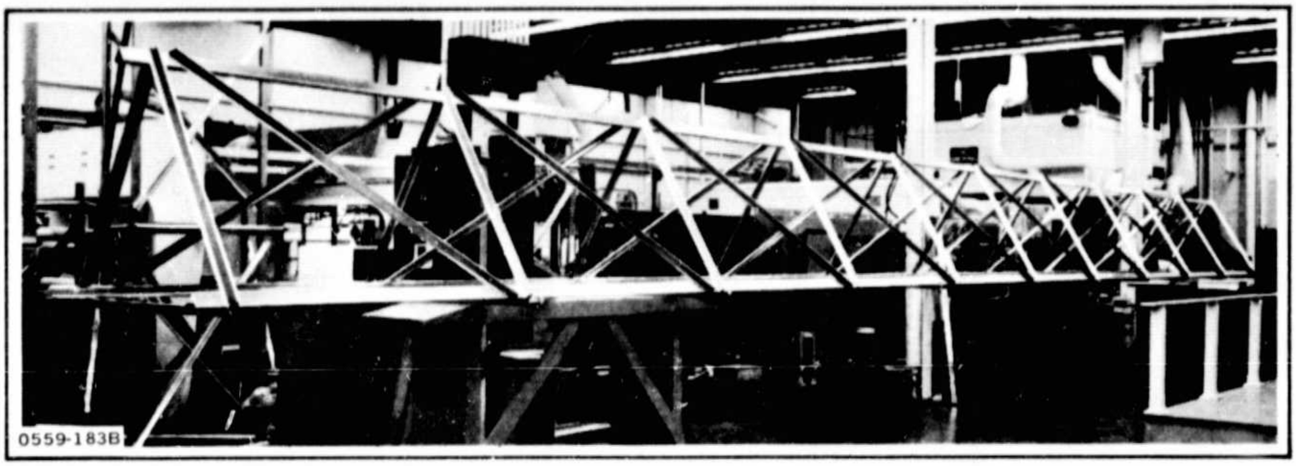


Fig. 3-21 Ten-Bay Beam

3.2.6.3 Fastening Cycle – Once the caps have been formed to the proper length, the computer directs the sequential operations necessary to insert and fasten the vertical and diagonal stiffeners. The computers (CPU) will direct a device to turn on or off and wait for a confidence signal that this action has occurred. When it has, it will direct the next sequence to be performed. To save time, some operations can be performed in parallel. An example is in the motion of the spotwelding electrodes, two can be moving up to position while the two which had been in position are moving to the retracted position. Approximately 80 actuators and 90 confidence signals are included in the control system.

4 - QUALITY ASSURANCE

The general object of quality control in this program was to assure the quality and success of the end product produced by the Space Fabrication Demonstration System. To achieve this goal, the design, construction, and testing of the beam builder was monitored throughout the program.

Individual components of the beam builder were inspected prior to assembly so as to assure conformance to print on specification requirements. Of significance were the following:

- Box Beam Weldments – A total of 58 weldments on box beams No. 1, 2, and 3 were magnetic particle inspected. No relevant indications were found on box beams No. 2 and 3. One weld on box beam No. 1 exhibited lack of fusion and some visual cluster porosity. This was considered acceptable for the ground test unit
- Bulkhead Plates – The tolerance requirements for the alignment holes were checked at the seller for each plate and found to within blueprint requirement
- Yoder Rolling Mill – Acceptance of the cap member roller mill was accomplished by source inspection of the mill at the seller in Cleveland, Ohio. The acceptance was based upon the satisfactory manufacture of the end product cap member by each of the mills. The first seller inspection revealed the cap members manufactured and witnessed by quality control were not within engineering drawing requirements. After readjusting the mill, a second source inspection of the seller showed the cap manufacture was of high quality with respect to dimensional requirements and overall geometry. The cap from Machine No. 1 had a slight negative bow of 0.062 in. in 8 ft which could be eliminated with light hand pressure. All other bow conditions from both machines were less than 0.10 in. and also could be eliminated with light hand pressure. Oil canning and flange waviness were minimal (less than 0.010 in. and infrequent.) The breakaway and running torque for both machines were found to be within acceptable limits. Based on the two seller surveillance visits and other supporting data, the machines were found to be acceptable
- Beam Builder Alignment – As the various sections of the beam builder were assembled, print tolerances were verified to assure proper functioning of the completed structure
- Beam – Because the production or manufacturing of a beam which would meet certain rigid dimensional and structural requirements was paramount to the success of the Space Fabrication Demonstration System, a major quality emphasis was placed on the end product to meet these specifications. Consequently, a series of material receiving inspection and in-process tests were conducted on the beam materials and sections of the beam itself, including:
  - Coil Aluminum Sheet – The material used for the cap was 2024-T3 aluminum purchased to QQA – 250/4. Actual chemical analysis specimen taken from one of the rolls established the validity of the material chemistry.

- <u>Beam Spotweld Tests</u> – In order to investigate the quality of the beam spotwelds, several welds taken randomly from a manufactured beam were metallurgically microsectioned and examined. The weld quality was of commercial standards as required by specification, but would not meet typical NASA or DoD requirements. It was judged that the spotwelds were of sufficient quality to meet the test requirements of the beam

- <u>Beam Dimensional Inspection – 6-m Machine Fabricated Beam</u>

  - <u>Cap</u> – The cap member dimensions were found to meet engineering structural requirements, though measurement of the two base angles was complicated by the rounded configuration of the base flats

  - <u>Brace Members</u> – Brace width dimensions were within acceptable limits, fitting well within their storage magazines and feed mechanisms

  - <u>Vertical Brace Spacing</u> – The vertical brace spacing of the machine fabricated beam to within 0.045 in. of print requirements

  - <u>Cap Member Spacing</u> – The cap spacing dimensions were good on the machine fabricated beam with measurements varying to within ±0.070 in. of print requirements

- <u>Length Measurements</u> – Part of the beam builder acceptance criteria included the conformance of a four-bay beam, a ten-bay beam, and three beam caps to the critical length dimensions required by the print. The results of these measurements are listed in Table 4-1. All measurements were taken along the length of the three caps for each beam and all were within acceptable tolerances.

Table 4-1 Length Dimensions of Beams & Caps

ITEM REQD	RESULTS		
	A	B	C
4-BAY BEAM	27′ 30/32″	27′ 29/32′	27′ 29/32′
10-BAY BEAM	50′ 24/16′	50′ 23/16′	50′ 23/16′
CAP MEMBERS	70′ 23/32′	70′ 22/32′	70′ 22/32′
0559-185B			

5 - CONCLUSIONS & RECOMMENDATIONS

5.1 CONCLUSIONS

The Automatic Beam Builder was developed, fabricated, and demonstrated within the established contract cost and schedule constraints. The ABB demonstrated the feasibility of:

- Producing lightweight (0.85 lb/ft) beams automatically within the required rate of 1 to 5 ft of completed beam per minute
- Producing structurally sound beams with an axial design ultimate load of 5540 N (1245 lb) based on the Grumman photovoltaic Satellite Solar Power System design reference structure.

Flight test demonstration of the aluminum ABB's operational capability in the space environment should be the next major milestone. This should be preceded by a balanced analysis and ground test program to develop the flight demonstration unit and establish the data base required for the flight test program.

5.2 RECOMMENDATIONS

The following recommendations will lead to an orderly and cost-effective flight demonstration program:

- ABB analysis and design effort to modify the primary and secondary structure for launch loads and lightweight considerations
- Loads and dynamics analysis to provide the overall dynamic model and verify the quasi-static loads of primary structure plus dynamic model of the various subsystems to verify launch, boost, and random vibration loads
- Design of launch locks to ensure post launch operational capability of Yoder mill assembly, cross brace magazine, carriage assembly, and weld clamp assembly
- System analysis and preliminary design to select and tailor flight test instrumentation, i.e., accelerometers, temperature sensors, strain gages, lightweight high frequency shakers, and electro-optical systems to provide beam structural and thermal characteristics
- A coordinated ground test program including thermal vacuum tests, ground vibration surveys, and water tank neutral buoyancy tests to provide preliminary verification of the analysis and establish baseline data for the flight tests.